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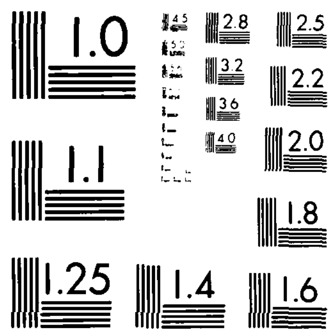

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ACCURACY AND OPERATIONAL USE OF MEDIUM AND EXTENDED RANGE NUMERICAL ATMOSPHERIC FORECASTS: A REVIEW

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The potential benefits of medium range (5-10 day) and extended range (10-15 day) atmospheric forecasts in support of the U.S. Navy are assessed. The present and likely near-future state of the art of medium range and extended range forecasting are surveyed, summarized, and related to specific operational requirements and applications of such forecasts. Conclusions regarding the required skill for longer-range forecasts are provided. Several issues relating to forecast system support at a central site, and to presentation, distribution and use of products, are presented.

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SECTION 1. SUMMARY

The potential of medium-range (5 to 10 days) and extended-range (10 to 15 days) forecasting is evaluated relative to the feasibility of numerical models and the operational benefit to the U.S. Navy. Both the present and near-future state-of-the-art of longer-range* numerical forecasting are evaluated in regards to accuracy in Section 2. The European Centre for Medium Range Weather Forecasts (ECMWF) continues to be the leader in this field of longer-range numerical forecasting. Section 3 presents the utilitarian aspect of medium-range and extended-range forecasting with respect to naval operations. Several Oceanography Command implications of medium-range forecasting are discussed in Section 4. Conclusions regarding the capabilities of numerical forecast models and the usefulness of medium-range and extended-range forecasts are presented in Section 5. The basic conclusion is that many aspects of naval operations could greatly benefit from accurate medium-range and extended-range forecasts. However, the lack of demonstrated skill of present numerical forecast models in the extended range suggests that efforts to provide an operational forecast capability be limited to the medium range.

Though medium-range forecasts can provide useful information to help guide future naval operations, this information will often not be presented in the form with which the typical operational user is now accustomed. Some training will be necessary to assist the users in interpreting the new output, especially time and space-averaged products, in order for this information to achieve its potential usefulness.

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* "Longer-range" is used throughout this report as a general term encompassing both the medium-range and the extended-range whenever a distinction between the two is unnecessary.

The final and principal recommendation is that the U.S. Navy proceed with plans for providing medium-range, operational forecasts and that, as an initial step, the new 9-layer version of the Navy Operational Global Atmospheric Prediction System (NOGAPS) be thoroughly evaluated as a medium-range prediction system.

SECTION 2. REVIEW OF MEDIUM AND EXTENDED-RANGE FORECASTING

<u>2.1 Predictability Aspects</u>. Any discussion of forecasting the atmospheric circulation in the longer ranges (5-15 days) must take into consideration the concept of predictability. Lorenz (1982a) defines the predictability of a system as the degree of accuracy with which it is possible to predict the state of the system in both the near and the distant future. There is an <u>intrinsic</u> limit to the accuracy of a forecast even when one has a <u>perfect</u> knowledge of the initial conditions, because of the nonlinear interactions between the scales of motion in the system and an incomplete knowledge of the governing equations. In a more practical sense, we acknowledge that the predictions will be based on an imperfect knowledge of the initial conditions. Gilchrist (1982) uses the term "deterministic predictability", which is defined to be the time it takes for initial state errors consistent with <u>observational</u> <u>accuracy</u> to grow to saturation values in a forecasting model. One recently developed practical measure of predictability is that used by the European Centre for Medium Range Weather Forecasts (ECMWF). Following Doos (1970), the ECMWF defines predictability in terms of the time when the prediction error reaches the climatic variance. A specific measure of "useful predictability" is the time when the anomaly correlation between observed and predicted deviations from climatology first reaches either 0.5 or 0.6 (Bengtsson, 1982a). Hollingsworth, et al, (1979) found this range of correlation values was justified by comparisons with subjective assessments of the forecasts carried out by some of the ECMWF member states.

Lorenz (1982a) points out that the deciding factor in predictability is the stability or instability of the system. Lorenz defines a realization of a deterministic system to be stable if the difference between this realization and any other realization remains small throughout the future, whenever the difference is sufficiently small at the present. In an unstable system, there are realizations whose distances from the given

realization is arbitrarily small at present, but exceed some pre-assigned value in the future. It is well known that the atmospheric circulation is frequently unstable in the sense that small disturbances will grow. In the mid-latitudes, the growth rate of baroclinically unstable perturbations is indeed comparable to the typical growth rate of forecast errors. Lorenz (1972) has also shown that barotropic instability of time-variable flow including migratory waves can also lead to a three-day error doubling time. The instabilities in the tropics with the largest growth rates are those related to convective processes. Therefore, one can anticipate that the predictability in the tropics will be smaller than in the midlatitudes.

The internal instabilities of the atmosphere may be cited as one reason why longer range weather forecasting is not possible by a summation of periodic signals. The atmosphere does have periodic components (especially diurnal and annual cycles) which are predictable at arbitrarily long ranges. However, the weather forecaster must predict the residual after the periodic components are subtracted from the total signal. This residual is aperiodic. Even though the external forcing of the atmosphere is periodic, the response will not be the same because of the internal instabilities. Lorenz (1969a) found only two pair of hemispheric patterns within a five-year set whose differences were as small as 62 percent of the difference between randomly chosen patterns. Furthermore, Lorenz estimated that 130 years of data would be needed to reduce this difference to 50 percent. Thus the initial difference between any two analogues is relatively large, and the difference between the analogue-predicted state and the observation generally must be large because of the inherent error growth rate. Numerical models which properly treat the atmospheric instabilities, and which incorporate the correct specification of the external forcing, are thus the best hope for achieving useful longer range predictions. Nevertheless, there is a limit to the length of such deterministic forecasts.

Lorenz (1969b) showed that the errors in the larger scales of motion doubled in a matter of days, whereas those in smaller scales doubled in hours, or even in minutes for the smallest scales of motion. More importantly, the errors in any scale quickly contributed to the growth of errors in adjacent scales. Even if there were no errors in the large scale, the errors in the smallest scales (unresolved in practical numerical weather prediction models) would progress rapidly upscale. It is also important to note that the energy levels in the atmosphere are smaller for shorter wavelengths. Thus, the errors "saturate" the smaller wavelengths more rapidly than the longer waves, which thus have longer predictability times. However, some of the operational prediction models did not exhibit this behavior. Lambert and Merilees (1978) showed that the Canadian hemispheric spectral model predicted the medium-scale waves better than the planetary waves. Somerville (1980) suggested that the use of hemispheric models, and perhaps an unsatisfactory treatment of tropical data or physical processes, could account for the instances of reduced predictability of the planetary waves.

Lorenz (1982a) suggests that the range of acceptable forecasting could possibly be extended by three days by cutting the observational error in half (if errors in the smaller scales were completely absent). Even larger improvements in observation-analysis system would lead to greater predictability. However, we must eventually reach a point where the errors in the initial state specification would be no larger than the errors that would be present anyway because of the smaller scales. After that point, further improvements in observations and analysis system would yield only minor improvements in medium and long-range prediction.

There are several reasons why the situation is not as clear as it might seem from the above discussion. The above error growth estimates are based on the growth of small errors due to

nonlinear scale interaction associated with advective processes only. Lorenz (1982a) points out that once the errors have become moderately large, the processes that are responsible for slowing and eventually stopping their growth may be other than advection. There are several slowly varying influences on atmospheric circulation. The moderating influence of the ocean heat source is one example. In addition, persistent sea-surface temperature anomalies may cause quasi-stationary circulations in the atmosphere, especially in the tropics. The extent of the sea ice and the snow cover over continents can also have a modulating effect on the atmospheric circulation.

Another factor favoring longer range predictability is the existence of atmospheric regimes. Lorenz (1982a) attributes this to a phenomenon called "almost intransitivity", in which the atmosphere can evolve readily from one pattern to another within the same regime, but only with some difficulty to a pattern in another regime. Gilchrist (1982) provides examples of "spells" of above or below normal surface temperature, which may correspond to a persistent weather type. The tendency for local positive or negative anomalies to persist indicates that medium-scale prediction may have more potential than the above error growth estimates would suggest. There are also global scale fluctuations which exhibit "almost intransitive" states. The quasi-biennial oscillation in the tropical stratosphere is a well-known example. The Southern Oscillation is another large spatial scale feature which, once established, exhibits a rather regular evolution. On the time-scale relevant to medium-range forecasting, the "blocking" phenomenom is of special interest. The capability to predict that a blocking pattern will develop, persist or dissipate would be a most valuable forecasting improvement.

The early estimates of the predictability of the atmosphere were based on "predictability experiments". Given a set of forecast equations, the set is solved twice with slightly

different specifications of the initial conditions. One then examines the differences between the solutions at different intervals to see whether the differences are increasing. Since the objective is to determine the growth rate of the differences, it is not essential that the initial errors be as large as the typical observational errors. Robinson (1967) had anticipated similar error growth rates based solely on the inapplicability of the typical numerical representation of an atmosphere that has a continuous spectrum of motion. The point is simply that there is an inherent growth of errors in any forecast model that will limit deterministic longer range forecasts.

Lorenz (1982b) has recently updated the estimates of predictability based on the ECMWF model. He derives both upper and lower bounds to atmospheric predictability over the globe, and separately for the Northern Hemisphere. The growth of the forecast error versus the verifying analyses is largest in the first 24 hours, and then the rate of error growth is gradually smaller through 10 days. Of course, the forecast errors eventually approach the difference between two randomly selected initial fields. Lorenz also plots the average difference between the j-day and k-day (j = k) prognoses. The rate of growth of this difference as k increases from 1 to 10 days represents the rate at which two solutions of the same system of equations - those of the model - diverge. Lorenz uses the difference between the upper and lower predictability bounds to estimate the ultimate length of skillful forecasts. The (over) optimistic view is that this limit is more than two weeks. Applied only to the Northern Hemisphere, Lorenz expects that eventually the 10-day forecasts could be as good as present ECMWF 7-day forecasts, and the 13.[illegible]-day forecasts as good as present 10-day forecasts. Furthermore, if the present 1-day root-mean-square error could be halved, the predictability of the model would be extended another two days. These estimates, with several caveats, are somewhat more encouraging than some of the pessimistic views expressed in recent years. The success of the ECMWF predictions has clearly

error could be due to the under representation of the height of the mountain ranges in the model - which led to the development of the "envelope orography" described above. Day-to-day variability in the growth of the systematic error, and thus also in the total error, may be due to the character of the zonal flow in the region of each mountain range. The authors suggest that if one knew the 1-day error and the mean circulation pattern, one could estimate the time evolution of the systematic error pattern (due to this effect) through the remainder of the forecast interval. However, experiments which included an envelope orography did not yield the expected reduction in the negative biases in the 1-day forecast over the major mountain ranges. In fact, the error pattern was changed in a rather complicated way. Nevertheless, the enhancement of the orography did have a beneficial impact upon the medium-range forecasts. The authors conclude that other equally important and potentially remediable source of error still exists in either the model formulation or in the initialized analyses.

Two other sources of systematic error - convection and surface processes - will be treated in the following subsection because they are particularly important in the tropics. In closing this subsection, it should be emphasized that some of the effects of systematic errors may be reduced by statistical post-processing. In fact, Lorenz (1982b) has demonstrated that the ECMWF 3-10 day forecasts could be improved by statistical regression. However, the better method is to seek and remove the sources of the systematic errors in the model. Considering the research into these errors by a number of centers, one can be optimistic that progress will be made in the next few years.

2.5 Tropical Influences on Medium-Range Prediction. It has been recognized since the early planning of the Global Atmospheric Research Program (GARP) that the tropics affect midlatitude weather on time scales beyond a few days. Thus, an early thrust in GARP was the planning and execution of a tropical experiment -

model (Ramanathan et al, 1982). The observed winter polar stratospheric temperatures are maintained by a delicate balance between longwave radiative cooling and heating by dynamical processes. Hence, proper treatments of wave/mean flow interactions and the diabatic processes are essential for capturing the observed winter circulation (Ramanathan, 1983).

Another model feature which is a likely contributor to the systematic errors is the parameterization of the planetary boundary layer (PBL). Randall (1982) has shown that an improved PBL representation resulted in an improved sea level pressure prediction. The global maps of the surface fluxes are also generally smoother with the new parameterization. Randall (1983) reported that stratiform cloudiness is excessively widespread in the lowest layer of the Goddard Laboratory for Atmospheric Science (GLAS) model. A similar problem occurs in some other general circulation models (probably including the NOGAPS). Some improvements are needed in the treatment of the processes by which water is transported upward from the lowest model layer. Two options being explored to improve the model forecasts are the incorporation of additional model levels near the surface or a higher order closure representation of the PBL.

Wallace, Tibaldi and Simmons (1983) illustrate the evolution of the systematic errors during the ECMWF 10-day forecasts. The error growth appears to be approximately linear in the first few days. In the latter part of the forecast interval, the systematic errors have a strong negative spatial correlation with the (time-averaged) stationary wave pattern. That is, it appears that the ECMWF model lacked sufficient forcing to maintain the stationary waves at the proper amplitude. Hollingsworth, et al, (1980) and Derome (1980) had earlier noticed this characteristic. The overly intense zonal wind also contributes to the systematic error pattern. It is important that this error has an equivalent barotropic structure with amplitude increasing with height. Wallace, Tibaldi and Simmons (1983) suggest that the systematic

models examined, there is a systematic trend towards low tropospheric temperatures. Except for the NCAR model, there is commonly a problem of cold stratospheric temperatures. It thus follows that the tropospheric jets will be too strong and extend too high into the stratosphere. The only model that properly simulates the polar night jet is that of NCAR. The surface westerlies around 45 degrees latitude during the winter season are systematically too strong in all models. Both the size and position of the stationary eddies are not well represented in many of the models. As mentioned above, the low pressure centers in the eastern North Atlantic and eastern North Pacific are too far to the east. Consequently, the westerly flow is too strong over the eastern Atlantic and western Europe, and across the northern Rockies. Most of the models tend to be deficient in low frequency eddy activity, which is important for simulating blocking events.

The commonality of the systematic errors in the various models indicates the need for examination of all aspects of the model system. Even the basic equation set must be considered as a source of error. Perhaps the most suspect aspect is the treatment of subgrid physical processes, such as the assumptions made in treating subgrid fluxes, friction, diffusion and convection. The sensitivity of the models to the treatment of moisture is relatively well known. Another disturbing aspect is that higher resolution models are sometimes found to have larger systematic errors (e.g. Cubasch, 1983). The low resolution spectral models exhibit a better treatment of the long waves and zonal flow. The reasons for the poor performance of the high resolution models is unclear, although it is possibly due to improper handling of the large scale forcing in the model.

As indicated above, the NCAR model is the only one which has a proper representation of the winter polar stratospheric temperatures and the polar night jet intensity. A key factor in this success is the incorporation of a refined cloud/radiation

error standard deviations reaches 10 m/s at 5.6, 3.4 and 2.7 days in 50% of the forecasts at 850, 500 and 200 mb, respectively. Corresponding values for persistence forecasts are 2.0, 0.7 and 0.5 days. Thus, the ECMWF does have skill in forecasting the vector wind.

Another useful representation of the accuracy of the ECMWF forecasts during 1980-81 is provided in terms of North Atlantic cyclone statistics (Akyildiz, 1983, unpublished Tech. Memo. No. 74, ECMWF). Tracks, central pressures, deepening and filling rates, translation speeds and life spans of cyclones were tabulated. The ECMWF forecasts had a tendency to shift cyclone tracks toward the south, especially after 4 days, except near Newfoundland where a significant northward shift occurred. A slow phase error is noted during the developing stages of cyclones. Both the deepening and filling rates are forecast to be less than the observed rates. Consequently, the amplitude of the model cyclones is relatively smaller during the first two or three days and relatively larger during the later stages. As Haseler (1983) points out, the surface stress will be too large along the cyclone tracks. The 5-day and 10-day forecasts missed most of the cyclone activity over the Mediterranean area, especially in the eastern part. These forecasts overestimate the secondary track from the east Atlantic towards the European continent, as well as the cyclonic activity over eastern Europe. A similar evaluation of the predicted cyclone tracks and life cycles in other areas of the globe would be particularly useful in determining the utility of such forecasts for the Navy.

2.4 <u>Effect of Systematic Errors in Medium-Range Forecasts.</u> Bengtsson points out in the introduction to the 1982 Workshop (ECMWF, 1983a) that the quality of the ECMWF medium-range forecasts is largely affected by systematic errors. Thus, an intercomparison was made of the performance of several models used for extended range forecasts and general circulation simulation, and in particular their systematic errors. Of the

the ECMWF system (and the other modifications during 1981) led to markedly improved predictions over the Southern Hemisphere in 1981 versus 1980. The most significant improvements are seen at 1000 mb, especially in the temperature scores.

A more recent comparison of the ECMWF forecasts in the region of New Zealand has been carried out by the New Zealand Meteorological Service (ECMWF Newsletter No. 20, April 1983). The ECMWF 2-day surface pressure predictions are slightly more skillful than the New Zealand manual 30-hour predictions, and the ECMWF 3-day predictions are as skillful as the 48-hour New Zealand numerical model predictions. This advantage at the surface is extended when the verification is over the Southwest Pacific region rather than just the immediate New Zealand area. At 500 mb, the ECMWF forecast at 96 hours is as skillful as the 48 hour New Zealand model. This independent verification study indicates the potential usefulness of a sophisticated global prediction model in the Southern Hemisphere.

The daily variation in the anomaly correlation scores is an important aspect to be understood by the forecasters who will be using the model output. Although the 3-day 500 mb forecasts in the Northern Hemisphere are above the 0.8 anomaly correlation score most of the time, the variability of the prediction skill increases markedly after this time. In 1981, only about 50% of the 6-day forecasts had anomaly correlations above 0.6. However, there are long episodes when the 5-7 day forecasts have anomaly correlation values above 0.5. In the Southern Hemisphere, the 2-day forecasts at 500 mb had scores above 0.8 in 75% of the cases, and 60% of the 4-day forecasts had scores above 0.6. In general, the predictive skill in the Southern Hemisphere is 1.5 to 2 days shorter than in the Northern Hemisphere.

An important consideration for the Navy is the skill of the wind forecasts. Niemenen (1983) shows the vector wind error growth with time over Europe during winter 1981. The vector

seasonal variations in the skill of the ECMWF model, with the summer skill being smaller. The month-to-month variability in the anomaly correlation score is as large as the seasonal variability. There is some indication that the ECMWF is more skillful during periods with more meridional flow, for example, during blocking regimes.

Bengtsson, et al, (1982) have described the usefulness of the ECMWF analyses and predictions in the Southern Hemisphere during the FGGE year. The impact of the observational data base, analyses and predictions during FGGE was particularly evident in the First Conference on Southern Hemisphere Meteorology (American Meteorological Society, 1983). Considering the Navy's requirements for global deployments, an understanding of Southern Hemisphere meteorology and an ability to forecast in that area is of some importance. As an indication of some of the newly revealed aspects, Bengtsson, et al, (1982) show that the intensity of the polar night jet in the Southern Hemisphere during July 1979 is 95 m/s, which is twice the value indicated by climatology. These high stratosphere wind speeds also determine the maximum time step allowed in the ECMWF model (S. Tibaldi, personal communication). Niemenen (1983) demonstrates that the annual mean anomaly correlation scores in the Southern Hemisphere are considerably lower than in the Northern Hemisphere. Over South America and South Africa the 500 mb anomaly correlation decreases to 60% at 4 days in both summer and winter. It is somewhat surprising that the 500 mb correlation score indicates a useful predictability to about 5 days over Australia during summer and only 3.7 days during winter. These 500 mb scores are better than at 1000 mb. One area of controversy is the beneficial effect of the drifting buoys deployed during the FGGE period. By the end of the period studied by Niemenen (1983), all of these buoys had ceased operation. Thus, the skill of the ECMWF model may have also decreased after 1981. However, other factors are also important. The introduction of the Australian surface observations manually derived from satellite data into

comparisons with the Hadley cells in the tropics (after 1 November 1982 the verifications have been relative to the analysis fields prior to the initialization). Verification statistics are prepared for 12 separate areas and in three latitudinal zones. The primary objective scores used for evaluating medium-range forecasts are the anomaly correlation and the standard deviation of the height errors.

Bengtsson (1982a, b), Bengtsson, et al, (1982), Simmons (1982) and Niemenen (1983) discuss the systematic errors in the ECMWF model. The predicted mean values of geopotential height and temperature are too low at the upper levels. This global error grows in time and reaches values of 4 degrees C when the integration is extended to 50 days. Large negative geopotential height errors are found over the eastern North Pacific and the eastern North Atlantic during winter. This model, as do other operational models, has excessive zonal mean flows and too weak eddy kinetic energy components. Generally, the lower troposphere is too dry and the upper troposphere and lower stratosphere are too moist. The origin of these systematic errors will be discussed further below.

Niemenen (1983) demonstrates the considerable error variations from region-to-region and from month-to-month. Only a few statistics from this extensive summary of forecast results will be presented here. The reader is referred to the original tables and figures for more complete statistics. In the winter season, the 60% anomaly correlation score at 500 mb is reached at day 6.0 for the North American region, at day 7.3 for the eastern Asia area and at day 5.3 for the European area. The winter anomaly correlations at 1000 mb are only slightly lower than the 500 mb values over Europe, whereas the value at 1000 mb over North America is only about 3.8 days. The summer anomaly correlations are generally at least 1 day less than the winter values. In the eastern Asia region, the decrease in skill at 500 mb during summer is nearly 3 days. Thus, there are large

the subgrid fluxes. Savijarvi (1981) shows that the analyzed annual mean generation and horizontal flux divergence of kinetic energy and the heating and temperature flux divergence over the North American region, the North Atlantic region and the European area are quite reasonable. The residuals of the energy budgets also represent the expected subgrid scale effects reasonably well. Corresponding analyses of the 3-day forecast fields reveal strong stratospheric cooling, insufficient heating over the ocean area and the slow spin-up of the condensation processes. The forecast surface friction is quite strong, whereas the dissipation maximum at the jet level is too weak.

Another analysis of the energy budget based on the ECMWF 12 GMT analyses during August 1980 - July 1981 has been completed by Oriol (1982). These statistics provide consistent calculations of the energetics in the Southern Hemisphere, although the reliability of these estimates in the relatively data-void Southern Hemisphere is certainly questionable. The availability of monthly energy budget estimates by wave number is also useful for illustrating atmospheric variability. Even larger variability is shown by the daily energy cycle quantities, and Oriol (1982) attempts to relate the time variations to synoptic events. The overall energy cycle deduced from the ECMWF analyses appear to agree well with earlier studies.

Niemenen (1983) presents a verification of the ECMWF forecast fields. Conventional objective scores such as correlation coefficient, RMS error, standard deviation of error and mean error are calculated for heights, temperatures, winds and relative humidities. A skill score is also provided for the height fields. Precipitation forecasts over Europe have been evaluated by Akesson (1981) and Johannessen (1982). Other surface parameters have been compared with observations at selected European sites by Akesson, et al (1982), Bottger and Gronaas (1982) and Pumpel (1982). The 1980-81 forecasts were verified against the initialized analyses, which does not allow

requirement for oceanographic forecasting with a similar set of global, regional and specialized predictions of ocean waves, currents and thermal structure. Thus, there is a competition for resources to support multiple forecast requirements at FNOC that is not felt at the ECMWF. Although it is very important for FNOC, with the assistance of the Naval Environmental Prediction Research Facility (NEPRF) and the Naval Ocean Research and Development Activity (NORDA), to improve and extend its ability to provide atmospheric and oceanographic forecasts to the fleet worldwide, this has to be balanced against the potential benefits of improved short-range guidance to specific units (for example, battle groups) at specific locations. It will be demonstrated below that the development of the ECMWF global model resulted in improved short-term forecasts as well as medium-range forecasts. The benefits of a very complete and sophisticated global model are also felt in the analyses through the data assimilation process. Furthermore, an accurate global model prediction can have a beneficial impact on the regional and specialized models via improved initial conditions and boundary conditions.

2.3 Accuracy of the ECMWF Model. Extensive performance statistics for the ECMWF model during 1980 and 1981 are now available. These will be used in this section as a baseline, but one must realize that the system changes introduced since then have improved the predictions. In addition to the standard verification and diagnostic package (Arpe, 1981), the ECMWF personnel have also developed limited-area energy budget programs for evaluation and improvement of the product (Savijarvi, 1981). The research group of Reading University has regularly evaluated 15-day means and variances of the ECMWF analyses to describe the large-scale evolution of the atmospheric circulation (B. Hoskins, personal communication).

The basic objective of the energetics studies of the ECMWF analyses is to determine if the analysis-initialization system produces a proper representation of the divergent components and

time the spectral version was adopted (see above), several other major changes were made. A hybrid vertical coordinate system (Simmons and Strufing, 1981) which resembles the usual sigma coordinate close to the ground, but reduces to a pressure coordinate at stratospheric levels, was adopted. The model was also extended to 16 layers in the vertical. Introduction of a more efficient time integration scheme, which uses a semi-implicit method to treat the advection of vorticity and moisture by the zonal mean flow, allowed a time step of 20 minutes. Another major change was the introduction of "envelope orography" (Wallace, Tibaldi, and Simmons, 1983). In this new orography, multiples of the standard deviation of the actual orography in the grid square are added to the mean to enhance the orographic forcing. A modification is necessary near coasts to reduce the variation of the spectrally fitted orography. The major objective of introducing the envelope orography was to improve the forecasts of the large-scale flow.

In summary, the development of a medium-range forecast capability at the ECMWF can serve as a useful guide as to the effort required to develop such a capability for the Navy. Although the Navy can benefit from the experience of ECMWF, the development of a medium-range forecasting capability will require a considerable long-term effort in terms of human and financial resources.

To be fair, it should be pointed out that the ECMWF is a single-task organization, whereas the Fleet Numerical Oceanography Center (FNOC) and the National Meteorological Center must support multiple forecast requirements. For example, the FNOC atmospheric prediction system presently has at least three tasks: (1) Global predictions with a global model for broad scale forecasts to five days; (2) Regional predictions with regional models for focused forecasts at shorter ranges; and (3) Special situation predictions with specialized models, such as the Nested Tropical Cyclone Model. In addition there is the

pole and equator . The ECMWF extensively tested Jarraud, et al, 1981; Girard and Jarraud, 1982 the spectral version. The spectral forecasts were superior at all atmospheric levels and all scales, but predominately for the long waves. The largest improvements were found after 4-5 days. The differences after 7 days were statistically insignificant. Girard and Jarraud conclude that the superiority of the spectral over the finite difference model is mainly due to numerical technique differences, in particular, the more accurate treatment of nonlinear advection. However, both models have negative phase errors and under-development of young and fast-moving lows, and positive phase errors and over-development of more mature systems. Tibaldi and Ji (1983) have recently published a case study of blocking in which it was demonstrated that the high resolution model (T63) produces a better prediction than the lower order (T40) model. They suggest that it was the ability of the higher resolution model to more correctly predict upstream cyclogenesis events that led to superior predictions of the blocking onset and maintenance.

Prediction of blocking events has been an important goal of the ECMWF group, because such an event can be a dominant feature of the European region weather. In one of the first ECMWF publications, Bengtsson (1981) documents the prediction of a blocking event beyond one week. This interest in simulating blocking has been continued by Tibaldi and Buzzi (1982) and Ji and Tibaldi (1982). These studies make use of the finite difference version of the high resolution ECMWF model, whereas many earlier studies of blocking have used relatively coarse models. The proper treatment of the earth's orography and of intense synoptic scale developments seem to require the high resolution.

Perhaps the best example of the dynamic nature of the ECMWF effort is the changes incorporated in the system during the spring of 1983 (ECMWF Newsletter, No. 20, April 1983). At the

1982). Perhaps the most important modification of the initialization scheme was the introduction of diabatic forcing in September 1982 to overcome the damping of the vertical motions in the original normal mode scheme (Hollingsworth and Cats, 1981).

It was mentioned above that all aspects of the ECMWF system have been examined for possible improvements. The ECMWF system has been used in data-impact studies, for example, the influence of cloud track wind data on analyses and medium-range forecasts (Kallberg, et al, 1982). The impact of any observation on the analysis depends not only on the quality of the observation as defined by the observation error statistics, but also on the internal constraints of the multivariate optimum interpolation scheme, such as the data selection procedures, and the quality of the first guess forecast defined by its error characteristics. Whether the observation will have an impact on the forecast depends on how much of the analysis impact is retained after the initialization and on how well the forecast model reacts to the analysis impact. Cats (1982) illustrates several cases in which the data selection procedure can have a significant impact. The problem of whether to accept an isolated observation over the ocean is a familiar one to the Navy geophysicist. Cats (1982) shows an example of two 10-day forecasts in which the only difference is the inclusion of a single ship surface pressure report. This initial perturbation in the analysis survives the initialization, and a propagating and growing wavetrain develops (as in Simmons and Hoskins, 1979). By the end of the 10-day forecast, this wavetrain extends half way around the globe. Cats concludes that with the present observational systems one should not expect to produce a forecast with a consistently high quality.

One of the major changes in the ECMWF system has been the introduction of a spectral version (T63 - triangular truncation, with maximum wavenumber 63) to replace the finite difference model (N48 - Arakawa C grid with 48 lines of points between the

changes will be described below -- these include the switch in 1983 from a finite difference to a spectral representation and introduction of the so-called "envelope orography".

It follows from items 2 and 3 in the previous paragraph that an assessment of the accuracy of the ECMWF system must also be continually updated. Summaries of the ECMWF progress and problem areas are best reflected in a series of reports of workshops and seminars (ECMWF, 1981a; 1981b; 1982; 1983a and b). Publications in scientific journals tend to lag by at least a year (Bengtsson, 1981a and b, 1982a; Hollingsworth, et al., 1980; Tibaldi and Ji, 1983). Bengtsson (1982b) reviews the problem areas in medium-range weather prediction when the ECMWF was established in 1975, and the operational status of the model in 1982. His report emphasizes the continual evolution of the ECMWF system and the need for future improvements. Over 30 changes were made in the operational forecasting system during the first two years of operation. A complete list of the modifications during 1980-81 are given in Appendix 2 of Niemenen (1983). An example is given by Simmons (1982) of a relatively minor programming change that resulted in a reduction in the systematic low temperature bias in the model stratosphere. Cats (1982) points out that the interpolation formula used in the stratosphere is not defined from physical considerations, and changing from one formula to another produces widely different analyses. A more important improvement in the forecast system resulted when the interpolation between the sigma and pressure coordinate was based on the analyzed increment instead of the full fields (Oriol, 1982). Other changes introduced in 1981 included the incorporation of the Australian surface pressure analyses as pseudo-observations, specification of the humidity from an objective analysis versus a six-hour forecast, and a more realistic topography (Oriol, 1982). Another simple change that resulted in improved forecasts in the tropics was the (correct) use of the virtual temperature in the hydrostatic equation to transform the analyzed height to the model temperature (Cats,

played an important role in developing this more encouraging outlook. This success also makes it reasonable to examine the potential benefits to the Navy of medium (5-10 days) and extended (10-15 days) range predictions, even though these predictions are not yet available.

As indicated above, the measure of useful predictions are a function of space and time (especially seasonal). The users of longer range forecasts must be aware of the inherent limitations. On the other hand, there is a considerable challange to recognize and exploit the usefulness of longer range predictions as they become available.

2.2 The ECMWF Experiment in Medium-Range Forecasting. It is indeed fortunate that guidance for assessing the potential for medium-range forecasting is available from the experience of the ECMWF. This agency is acknowledged to be the leader in medium-range forecasting, and one is able to trace the development effort that was required to achieve this leadership position via many internal and external publications. Because of the likely similarities in the steps that will be required to provide a medium-range forecasting capability to meet Navy needs, it is useful to review the ECMWF experiment.

Perhaps the most relevant overall impressions gained from a review of the ECMWF effort are: (1) A long-term investment of people and resources dedicated to a single effort was required. The ECMWF was established in 1975 and the forecasts did not become operational until August 1979. (2) All aspects of the ECMWF system (data-impact studies, objective analysis and initialization, numerical techniques and dissemination of the product) have been scrutinized for potential improvements. In most cases, the impact of each aspect has been quantitatively assessed by ECMWF with a detailed verification and diagnostics package (Arpe, 1981). (3) Several major revisions of the model have been required to improve the product. Some of the major

GARP Atlantic Tropical Experiment (GATE). A key aspect of GATE was to understand and improve the modeling of convective heat release. In addition, the GATE observations provided initial and verifying data for numerical modeling of the tropical circulation (Krishnamurti, et al, 1979). The First GARP Global Experiment (FGGE) also contained a strong tropical component. During the Summer Monsoon Experiment and Winter Monsoon Experiment, special observing periods provided enhanced data collections which are useful for testing tropical (or global) numerical prediction models. The ECMWF is one of the few centers producing tropical analyses and predictions on a routine, operational basis. Thus, it is of interest to see how effective these tropical predictions are, and how the tropical circulations influence the quality of midlatitude forecasts on medium time scales.

The tropical region is a primary source of heat and westerly momentum for the global zonal mean circulation. Perhaps the most exciting development in tropical meteorology in recent years has been the understanding of how the tropics influence the quasi-stationary waves in the midlatitudes (Wallace and Gutzler, 1981; Horel and Wallace, 1981). A teleconnection pattern that has been associated with the theory of latitudinal Rossby-wave propagation can account for tropical influences reaching the midlatitudes in less than a week (Hoskins and Karoly, 1981; Webster, 1981; Simmons, Wallace and Branstator, 1983). There can also be a tropical influence on the equatorward limits of deep midlatitude troughs, that is, on transient perturbations of the midlatitude circulation. Haseler (1982) found that the largest impact in a small set (seven cases) was found when tropical features interacted with deep midlatitude troughs. Modification of the phase tilt of these troughs led to significant differences in the evolution of the flow in the middle and high latitudes. Finally, the movement of tropical cyclones into the middle latitudes is cited (ECMWF, 1981b) as a cause of the relatively poor performance of the ECMWF system during September 1980.

Two recent simulations with the Goddard Laboratory for Atmospheric Science model has demonstrated the influence of the tropics on the prediction of the planetary waves (Baker and Paegle, 1983; Paegle and Baker, 1983). In the first case, tropical wind data are inserted as part of the assimilation to determine the contribution to the long waves. Differences present in the initial divergent wind field are found largely confined to the tropics, whereas significant differences in the rotational wind field are found at all latitudes after 72 hours. In the second set of simulations, the latent heating in the tropical belt from 20 degrees South to 20 degrees North is suppressed. The purpose of this extreme test is to determine the nature of the effect and the rate that this effect propagates into the midlatitudes. The time scale of the response in the tropics is less than 12 hours, whereas 72-120 hours are required for midlatitude response. The response is a function of the zonal flow pattern in a manner consistent with the theories of Hoskins and Karoly (1981) and Webster (1981).

Several studies (Bengtsson, et al, 1982; Shukla, 1981; Shaw, 1981) have indicated that the predictability of the tropical atmosphere is considerably less than in the extratropics. Most of the synoptic waves in the tropics have small amplitudes. Thus the errors of observations are already close to the typical variance associated with the synoptic waves. Because latent heat of condensation is the primary energy source for tropical circulations and the growth rate of condensation-driven instabilities is much larger than for extratropical instability mechanisms, the predictability is expected to have a shorter range in the tropics. Finally, the smaller horizontal scales of tropical waves and the embedded mesoscale circulations are also consistent with a smaller predictability.

In practice, the estimates of useful forecasts range from 3-4 days (Bengtsson et al, 1982) to 1-2 days (Heckley, 1983). Shaw (1981) examines ECMWF analyses and forecasts during the southwest

monsoon and the northeast monsoon. Shaw finds in each case that the forecasts are not even as good as a persistence forecast! The large systematic error in the ECMWF forecasts of the southwest monsoon flow have a number of similarities with the British Meteorological Office simulations (Gilchrist, 1977). There is a systematic reduction of the nondivergent mass transfer at 850 mb across the equator. The overall monsoon flow is changed toward a more zonal flow, with a much greater longitudinal extent than is indicated in the analyzed fields. The 3-day forecast of the 200 mb easterly jet north of the equator is also exaggerated. Shaw demonstrates that the low-level flow can be markedly improved by revising the topography adjacent to the Arabian Sea and by changing the soil water content distribution. Another serious problem in the early tropical forecasts at the ECMWF was the tendency to generate intense grid point storms (Shaw, 1981). The rainfall predictions in the northeast monsoon were frequently dominated by these spurious vortices.

Hollingsworth and Cats (1981) indicate that most of the early ECMWF forecasts also exhibited problems in maintaining the tropical circulation in the first few days of integration. One problem was that the subtropical anticyclones lost strength and the trade winds diminished in intensity in the first few days, rather than displaying the high steadiness observed in nature. The trade winds did increase to the proper strength around day six. A possible cause of this behavior is the Kuo convective scheme. The authors show that the vertical thermal structure in the analyses is abnormally buoyant, and the buoyancy at the unstable points is actually increased with time. Evidently the convection scheme releases insufficient precipitation, except at single grid points, so that by the end of the forecast there appears to be a tendency to concentrate the tropical convection in a single area.

The ECMWF has also tested a version of the Arakawa-Schubert

latent heat parameterization (Tiedtke, 1983). In an experiment with FGGE data during February March 1979, there was a large difference in the simulated mean flow in the tropics and in the extratropics compared to the operational model (Kuo parameterization). Development of a strong ridge over the eastern Atlantic and western Europe seemed to be teleconnected to a more intense heat source over South America which is associated with deep convection in the Arakawa-Schubert scheme. However, it appeared that the associated precipitation rates over South America and Africa were excessive. The inherent tendency of the Arakawa-Schubert scheme to dry out the atmosphere led to smaller cloud amounts. Thus, more solar radiative energy was absorbed at the surface, more evapotranspiration occurred, and this drove moist convection. Tiedtke found no conclusive evidence to favor the Arakawa-Schubert scheme over the Kuo convection scheme.

Hollingsworth and Cats (1981) also examine the possible role of the nonlinear normal mode initialization scheme in causing the systematic errors in the tropics. In the original formulation of the initialization, there was a severe damping of the large scale tropical divergence field. To preserve the divergence in the tropics, one may either include the diabatic forcing in the initialization or reduce the effect of the initialization by doing it on fewer modes. It was necessary to initialize vertical modes 1 and 2 to eliminate noise in the surface pressure tendency during the 6-hour data assimilation cycle, particularly for the low wave numbers. For higher wave numbers, more vertical modes were included to allow a two-layer convergence/divergence pattern to be maintained. Although the above changes were effective in the first two days of the forecasts, it appeared that other mechanisms became dominant and contributed to systematic error growth. Hollingsworth and Cats imply that the initial divergence field is not too important, because the divergence field develops quickly during the forecast. This appears to conflict with the conclusions of Krishnamurti and Ramanathan (1981), who demonstrate that the specification of divergence and humidity is

very important and greatly affects the forecast in the southwest monsoon area.

Rowntree (1983) has used the British Meteorological Office model to do several tests of the sensitivity to land surface processes. Surface albedo is of major importance in determining the absorption of solar energy. Other surface parameters are the emissivity and the roughness length. However, the most important factor is the soil water content. Bengtsson (1982b) states that for medium-range prediction it is probably more important to know the soil water or the potential evapotranspiration than to know the water vapor in the atmosphere! Rowntree finds clearly defined responses to planetary scale variations of albedo and soil moisture, and to regional anomalies in soil moisture. Unfortunately, these quantities are not directly observed, so the true effect of anomalous soil processes is unknown.

Although instabilities associated with convective heat release contribute to a reduced predictability in the tropics, Shukla (1981) maintains that it is the quasi-steady components of the tropical heat sources that are important in affecting the midlatitude circulation. Since the quasi-steady heat sources respond to slowly varying boundary conditions (such as sea-surface temperature and ground wetness conditions), it is possible that the time-averaged tropical circulation has some useful predictability. Although the tropical atmosphere is deterministically unpredictable after a few days, its influence on the middle latitude circulation might be calculated by prescribing the observed structure and intensity of the tropical heat sources (Shukla, 1981). Attempts to evaluate the effect on the midlatitude circulation by relaxing the predicted tropical fields toward the analyzed fields have been made by Simmons (1981) and Haseler (1982). It is clear from these experiments that a better understanding of the mechanisms by which the midlatitude circulation responses to the tropical forcing is necessary, because sometimes the response is negligible and in

other cases significant improvements occur.

The long list of deficiencies and recommendations to improve tropical prediction (see introduction to ECMWF, 1981b) is an indication of the need for considerable research and development in this area. It is clear that predictability of the tropical circulation is less than in the midlatitudes. It may be true that new measures of the predictability, or the usefulness, of the tropical forecasts are required. Anthes (1983) has recently made such an argument for mesoscale predictability, and some of his suggested measures may be useful for assessing tropical predictability.

2.6 Outlook for Extended-Range Predictions. It is only recently that comprehensive dynamical models have been applied to the problem of predicting short-term climatic variations (defined to be periods longer than deterministic predictions are valid). A pioneering effort was the attempt of Miyakoda (1972), which stimulated the planning for the FGGE and also constituted a very important impetus in setting up the ECMWF (Bengtsson, 1982b). A more common approach to forecasting beyond the deterministic range has been statistical prediction (see reviews by Nicholls, 1980; Namias, 1981; and Namias and Cayan, 1981). In a recent review of both approaches, Barnett and Somerville (1983) suggest that a blend of statistical and dynamical approaches will be necessary for the short-term climate prediction problem.

There have been several "brute-force" integrations of general circulation models for extended periods. Spar, et al, (1976, 1978) and Spar and Lutz (1979) applied the Goddard Institute for Space Studies model to 30-day forecasts. Although the global or hemispheric predictions had some skill relative to climatology, the regional anomalies were not well predicted. This was one of the first attempts to test dynamically the effect of anomalous sea-surface temperatures. Gilchrist (1977) also found inconclusive results in attempting forecasts with the

actual rather than the climatological sea-surface temperature. Miyakoda, et al, (1979) and Miyakoda and Strickler (1981) extended the earlier work by Miyakoda (1972) to include consideration of summer predictions. More recently, Miyakoda, et al, (1983) have made experimental 30-day predictions with several general circulation model versions. Different numerical methods (spectral versus finite difference), resolutions and treatments of the physical processes were used. The most successful forecasts were with a high resolution model with relatively advanced physics. Although the major blocking event during January 1977 is clearly a special situation, it is encouraging to find that sophisticated models appear to be capable of extended (10-15 days and perhaps 30 day) forecasts in certain conditions. It might be noted that climatological sea-surface temperatures were used in these predictions.

Miyakoda and Chao (1982) distinguish between free-mode anomalies that will result even if the external forcing is specified from climatology and forced-mode anomalies that result from non-climatological forcing. The larger the fraction of the atmospheric variability that is associated with the free modes, the less favorable the outlook for extended-range forecasting. As we have seen earlier, if the internal instabilities determine the atmospheric variability irrespective of the surface forcing conditions, the growth rate of the errors will be so large that there will be limited predictability. Egger and Schilling (1983) examine theoretical bases for estimating the errors in dynamic model extended forecasts. They state that even a high resolution model can not provide deterministic forecasts beyond several days (it should be emphasized that this statement applies to a barotropic model without surface forcing). Due to the unpredictable nature of the scale interaction in this theory, they conclude that there is little hope for satisfactory skill at extended ranges (say 15 days) with a dynamical model. On the other hand, the external forcing associated with events such as the Southern Oscillation definitely contributes to the generation

and maintenance of standing and transient planetary waves.

Madden (1982a and b) has stated that the task of improving extended-range predictions is one of allotting more and more of the "potentially predictable" component to the "predictable signal". In his terms, one attempts to minimize the difference between the effective noise and the estimated climate noise. Madden and Shea (1978) have estimated the climate noise as the natural variability of the monthly means. They show that there is large seasonal and geographic variability in these estimates. The potential predictability is the ratio of the interannual variance to the climate noise. According to this definition, large areas of the midlatitude ocean have no monthly potential predictability. If one can apply these estimates to the outlook for extended-range forecasting, this result has important implications for the Navy. Shukla (1983) has recently disputed Madden's estimates as being too pessimistic (see also the reply by Madden, 1983).

Shukla (1981) has provided a more optimistic estimate of the predictability for extended forecasts of mean quantities. He made nine 30-day integrations which differed only in the initial conditions. The effects of different observed initial states were larger than the effects caused by adding simulated observational errors. Shukla concluded that the planetary wave scales were potentially predictable for at least one month. Miyakoda and Chao (1982) also report a comparison of 30-day runs with three slightly different initial conditions. The model skill estimates begin to spread considerably after 10-15 days, so that one could not be confident that a single realization of the initial conditions would give an adequate 30-day forecast. One might consider a Monte Carlo type of approach with an ensemble of different initial conditions. Leith (1974) has suggested that at least eight samples would be adequate to establish a statistically stable result. This is clearly an expensive proposition if a sophisticated model is to be used.

Miyakoda and Chao (1982) demonstrate the increased predictability of time-mean values relative to predictions at discrete intervals. As had earlier been demonstrated by Smagorinsky (1969) and Gilchrist (1977), the predictability is raised as the averaging length is increased. Not only is the root-mean-square error decreased, but the score is also improved in terms of correlation coefficients. The use of time-mean values is well established in practical applications of extended forecasting. An averaging method called lagged-averaged forecasts has recently been proposed by Hoffman and Kalnay-Rivas (1983). In this case, a series of forecasts verifying at the same time are subjected to a weighted average as an alternative to the Monte Carlo approach described above.

To close this section on a positive note, there are strong statistical and some dynamical modeling studies that demonstrate the influence of external forcing (especially tropical sea-surface temperature anomalies) on short-term climate variability. Shukla (1981) has noted that additional predictability should be associated with these boundary forcings, at least for the time-mean circulations in the tropics (Charney and Shukla, 1981). A successful simulation of drought-like conditions over Northeast Brazil due to sea-surface temperature forcing has been reported by Moura and Shukla ([illegible]). If it can be demonstrated that improved dynamical extended-range predictions result from time-dependent sea-surface temperatures, then coupled atmospheric-ocean models will be required. Such models will require consideration of numerous additional factors described by Elsberry, et al, (1982) and Rosmond, et al, (1983).

The ECMWF is likely to assume a leadership role in experimental extended forecasts based on dynamical models. With the enhancement of their computer resources, a plan is being made to regularly extend the predictions to perhaps 30 days (S. Tibaldi, personal communication). This will provide a large set

of predictions that will provide a basis for systematically evaluating the practicality and usefulness of forecasts beyond 10 days. Again, the Navy may benefit by using the experience of the ECMWF as a guide.

2.7 Summary. The primary results of the review of medium and extended-range forecasts are summarized as follows:

a. Predictability studies have indicated that there is an ultimate limit to the period of deterministic forecasts. This limit is a function of the synoptic situation and thus will be different from day-to-day, season-to-season and region-to-region. A particular example is the marked reduction in predictability of the tropical circulations, if the predictability is measured in terms of the root-mean-square errors as is commonly done for midlatitude circulations. It has also been demonstrated that the predictability of the planetary scale waves should be greater than for the synoptic or shorter scale waves.

b. The experience of the ECMWF in making 10-day forecasts has led to considerable optimism for accurate medium-range forecasts in the midlatitudes. This experience can serve as a useful guide to the Navy in providing a medium-range forecast capability.

c. The length of useful ECMWF forecasts has been steadily improved in recent years. Although there are situations in which the forecasts are markedly less useful, there are also extended periods in which the midlatitude forecasts remain useful to 10 days and beyond. No method has been developed and tested to determine on the basis of the 1-day forecast error whether the medium-range forecast will be good or bad. Since the error growth depends on factors in addition to observational errors, an excellent 1-day forecast does not guarantee a good medium-range forecast. It does appear likely that a poor 1-day forecast due to an improper specification of the initial conditions will have

an increasingly large error with time.

d. The accuracy of the ECMWF forecasts in the Northern Hemisphere is at least one day greater than in the Southern Hemisphere. This demonstrates the importance of an improved observational base for improved medium-range forecasts. Further improvements in the observation-analysis system would result in additional gains in forecast accuracy.

e. Systematic errors in the numerical model are one of the largest contributors to medium-range forecast error. It follows that identification and reduction of the systematic errors should have a high priority in the effort to extend the length of useful forecasts.

f. Systematic errors in the model are particularly damaging for tropical forecasts. The drift toward the "model climate" is particularly rapid in tropical regions. Not only does this drift cause large systematic errors in the tropics, but the predictions of the long wave structure in midlatitudes can also be adversely affected by tropical errors within 4-7 days in certain situations. It appears that considerable research on convective heating and soil moisture parameterizations is required to improve tropical forecasts.

g. The possibility of useful extended-range forecasts by dynamical models has only recently been proposed. The optimistic view is that there are some situations in which the predictions of the planetary waves may be useful to 15 days, and perhaps to even 30 days. Outlooks in these ranges must be based on time averages of the predictions and the guidance would be directed to regions rather than specific locations.

SECTION 3. USES FOR MEDIUM-RANGE AND EXTENDED-RANGE NUMERICAL FORECASTS

3.1 Introduction. Longer-range forecasts have been prepared for a number of years by the National Weather Service (formerly the Weather Bureau). The extended forecast branch of that service's National Meteorological Center (NMC) was preparing a manual "five day series" synoptic forecast sequence three times per week at least as far back as the early sixties. Periodic fifteen and thirty day temperature and precipitation outlooks were also prepared by the same personnel. Over the years deterministic numerical model guidance has played an increasing role in such products - first out to five days and now out as far as ten. Reflecting this trend, the extended forecast branch has been absorbed within NMC's Climate Analysis group which now prepares monthly and seasonal (90 day) outlooks. Responsibility for three to five day temperature and precipitation forecasts and also for six to ten day temperature and precipitation anomaly predictions is now assigned to the Forecast Division. A useful summary of long-range prediction procedures, including the applications of NMC 3-5 day, 6-10 day, 30-day and 90-day forecast products is given by Harnack (1981). Such products serve primarily the greater public interest in the fifty states. In addition to radio and television public service applications, considerable use is made of such material by agriculture, energy (including public utility) and construction industry interests.

It is of some interest to consider what uses have been made of the ECMWF 10-day forecasts since the products became available in August 1979. Many of the comments below are based on interviews with ECMWF personnel during August 1983. Two categories of ECMWF Member States (the 17 mostly Western European nations who sponsor and fund the Centre) are evident. A few Members (for example, Germany, England and France) have extensive experience in numerical weather prediction and have their own sophisticated short-range prediction models. These Members tend

to use the ECMWF predictions only beyond the time interval of their own forecast models. Other Members rely on the ECMWF forecasts for both their short-term and their long-term guidance. An example is the report of the uses that Austria makes of the ECMWF products (ECMWF Newsletter No. 18, December 1982). Austria chooses to receive a full suite of products to 84 hours, and then only the 1000, 850 and 500 mb heights at 96 hours, 120 hours, 144 hours and 168 hours. Austrian public forecasts are generally issued only to 72 hours, except that outlooks to 5 days are issued on Monday and Thursday of each week. This is only one example, and other states do make use of the forecasts beyond 5 days. The forecasts beyond 7 days are generally regarded as experimental and not many of the Members choose to receive the products in this time range. However, the 5-10 day mean fields are widely distributed, probably because of the experience in the United States with the NMC mean fields.

A seminar was held to assist the Member States in the use of the ECMWF products (ECMWF, 1983b). One of the difficulties has been to identify specific public agencies that can use 10-day forecasts. The most likely applications are thought to be in agriculture, energy and transport. The Italian hydroelectric power agency is attempting to use the precipitation forecasts for power generation planning. Another attempt in the Netherlands is to use the 5-day mean 500 mb fields to develop an analog technique to predict the rain during the period. Other plans are indicated in the workshop proceedings.

Bengtsson (1982a) shows an example of a skillful "meteogram" in which 7-day forecasts of total cloud cover, temperature at 2m, precipitation, surface pressure and surface winds are interpolated to a specific site (Rome). No statistical corrections are applied, even though the model does not include a diurnal cycle. The ECMWF has been archiving observations and grid point fields since March 1981 to assist the Member States in developing model output statistics programs to forecast

conditions at selected sites. It appears that this is one way that ECMWF can develop interest in their product and increase customer acceptance.

The USAF Global Weather Center at Offutt Air Force Base prepares detailed medium-range (10 day) forecasts of "sensible weather" for several Northern Hemisphere locations but the skill of these has not been objectively evaluated.

The Navy's potential benefits from medium-range and extended-range forecasts are varied and plentiful, but the requirements for such longer-range forecasts are at best understated. The latest Annual Status Report of Oceanographic/Meteorological Requirements (OPNAV 3160-3 dated March 1983) summarizes 79 meteorological and 79 oceanographic requirements submitted by end-users of forecast products, such as the Fleet Commanders in Chief. Only six of these state or strongly imply a requirement for longer-range predictions. One (LANT MET 77 15) addresses improved accuracy and resolution of synoptic and mesoscale wind forecasts for aircraft carrier flight planning. The subject of LANT MET 81 08 is improved long-range weather and communication path reliability forecasts, and SSPO MET 82 07 suggests extending the forecast period for SLBM (sea launched ballistic missile) support. Two requirements (PAC OCEN 80 09 and LANT OCEN 80 17) discusses tactical (detection/counter-detection) routing for wartime convoys and task groups. NPOC MET 81 01, by addressing development of ice forecast models for the polar regions, presupposes some medium-range skill in forecasting upper boundary conditions for the ice models. The remaining 152 requirements typically address improving the precision and packaging of shorter-range predictions. The Naval Oceanography Command Mid-Range Objectives 1980-1990 dated 31 March 1980 targets a capability to "increase forecast accuracy such that skill (an advantage over climatology or persistence) is realized out to 4-5 days by 1980 and to 10-15 days by 1985", but provides no further discussion.

ranges constitute "near", "below" or "much below" normal conditions. Such distinctions will of course have to be understood by the "consumer" as well as by the "forecaster".

e. Compound condition parameters present two complications. First because they may depend upon the simultaneous occurrence of two loosely correlated events (for example freezing temperatures and winds greater than twenty knots) the likelihood of the compound event may be difficult to establish. A sixty percent expectency of freezing temperatures and a sixty percent expectency of strong enough winds does not yield a thirty-six percent chance of ice accretion (the straightforward compound probability) since the two conditions are not fully independent. The second complication is that some compound parameters are weapon/platform/system characteristic dependent. Trafficability, as indicated in Table 3-01, will depend on the vehicle involved (its weight, load, and tires or tracks). "Iced-in" susceptibility which in the fall of 1983 was very high for the Russian arctic fleet, will depend on hull type and power as well as on winds and temperature. Such operational considerations if "programmed" will require operational system characteristic data not presently available at FNOC or the Ocean Centers.

3.3.2 Presentation. It has already been suggested that a logical way to present longer-range forecast information is as explicit ranges of (most probable) values or as implicit ranges in adjective-modified, condition parameter terms. However, this does not sufficiently address the basic forecast information (or model variables) involved or the final formats used to transfer or display the longer-range forecast.

There are several ways to obtain a probable range of values.

require objective, quantitative determination.

b. A subjective descriptor will derive from _very imprecisely_ forecasting the likely value of a variable and then fitting that value into a table of value ranges which equate to an adjective descriptor. For example, suppose the model variables u and v correspond to an absolute windspeed of 12 meters per second and past verifications of previous forecasts have established a standard deviation of three meters per second. One could then specify to some confidence level that the observed wind speed will be in the vicinity of 18 to 30 knots (9 to 15 m/s), or Beaufort force five to force seven. This information could then be further converted to "strong winds" (as opposed, perhaps, to "light winds", "gale winds" or "storm winds").

c. Not all of the weather parameters listed are common prognostic variables. For example: only wind, temperature and large scale precipitation are directly computed by the NOGAPS forecast model. Any visibility and cloud predictions must result from some probably complex calculations based upon the distribution of moisture (mixing ratio) within model time and space. Precipitation type is a function of the temperature field and cloud type parameterizations. Such derivations will clearly require the use of Model Output Statistics (MOS) techniques to establish objective, quantitative relationships between the model's forecast variables and the desired, but unforecast, "sensible weather" parameters.

d. If a choice is made to relate certain condition parameters to climatological averages then it becomes necessary to know what the "normal" temperature or precipitation values are, as well as what departure

WEATHER PARAMETERS	CONDITION PARAMETERS
BASIC PARAMETERS	
Storm Track	Storminess
Vector wind (speed & direction)	Windiness
Temperature	Coldness/Warmness
Clouds (type, amount, bases and tops)	Cloudiness
Precipitation (type and rate or accumulation)	Raininess/Snowiness/Dryness
Visibility	Clearness/Haziness/Fogginess
Waves (sea, swell, surf - height, period & direction)	Roughness
COMPOUND PARAMETERS	
Ice Accretion Rate - based on wind speed, air temperature and water temperature.	Trafficability - based on temperature, on terrain composition and topography, and on mobile platform(s) involved.

TABLE 3-11. Basic Weather and Condition Parameters and Compound Parameter Examples.

Model variables are quantitative and application independent (20 meters per second, 270 degrees kelvin). Condition parameters are qualitative and often application dependent (gale winds, moderate ice accretion). Weather parameters tend to be quantitative and application oriented (surface winds 35 to 45 knots, temperatures in mid-twenties).

Model variables may be distributed in graphic "weather map" form for use by the "forecaster" but they are seldom passed on to the operational "consumer" of the forecast. Weather parameters are usually derived from model output by the "prediction system" software, then distributed to the "forecaster" and, sometimes, distributed directly to the "consumer". Condition parameters are presently subjectively derived by the "forecaster" from model variables or from weather parameters. Since most forecasts are now short-range and since most short-range forecasts are weather parameter oriented this situation is very satisfactory. However, it is expected that <u>condition parameters will dominate longer-range forecast products</u>. This has certain operational implications for the Naval Oceanography Command which will be discussed in Section 4 of this document.

Table 3-01 lists the most commonly forecast basic weather parameters and their condition parameters counterparts. Also included for discussion are examples of compound parameters. Some observations concerning the parameters:

a. The "-ness" endings on the condition parameters properly imply a qualitative vice quantitative evaluation, for example rough versus smooth, windy versus calm, etc. These descriptors of course lead to modifiers such as very rough, mostly calm or unseasonably cold. But such modifiers in turn presuppose some objective way to distinguish between rough and very rough, between seasonably cold and unseasonably cold. Thus our subjective, qualitative condition parameters ultimately

undertaken by the navy are subject to the special hazards of seas, surf, surge and salt spray.

Ceremony planning is a non-trivial consideration at most naval stations. Regardless of the occasion - VIP visit, personnel inspection, change-of-command - the location must be chosen well in advance so invitations and schedules can be issued, so canopies can be erected, bunting hung, public address equipment rigged, etc. Reliable medium or extended-range forecasts could preclude prescribing an inappropriate uniform or outdoor location, and avoid rerigging at the last minute or unnecessary indoor and outdoor platforms "just to be safe".

3.3 Content and Format. The substance and form of longer-range (medium-range or extended-range) forecast products should be substantially different from the familiar short-range products. Briefly, the longer-range product will be less specific as to time and place, will be less categorical and will be stated in terms of departures from normal rather than as changes from "today". For example, a short-range "NAS Norfolk: cloudy, ceiling lowering to 1000 feet and winds increasing to Northwest, 25 knots in early morning, low temperature 28, tomorrow's high in mid forties" might be compared to a longer-range "Western Atlantic: gales likely at mid-week, temps near normal. End-of-week clearing with winds and temps well below normal".

3.3.1 Parameters. For this discussion a distinction is made between: (1) forecast model variables (temperature, wind components, moisture and height) which apply at a model coordinate after a specific integration time step; (2) weather parameters such as point-in-time-and-space vector wind, or precipitation accumulated over a period of time which are derived directly from model output; and (3) model output related, operationally oriented condition parameters such as storminess, iciness or trafficability.

or something similar. Temperature and precipitation outlooks are helpful when scheduling loads and offloads. If not done at an established supply base or depot, appropriate temporary runwayside or deckside storage may have to be prearranged. Ice or freezing conditions can present a personal safety, as well as a quality of goods, hazard. Unseasonable heat can increase air-conditioned storage loads or cause breakdown and perishable losses.

As mentioned earlier, underway replenishment usually involves several units and days-in-advance scheduling of time and place. But also involved is the scheduling of order alongside and time alongside so that requisitioned consumables, spare parts, mail and movies can be properly staged and expeditiously passed from ship to ship. High winds and seas and precipitation present hazards and cause discomforts and delays which should be avoided.

3.2.5 Shore Facility Applications. Several shore facility applications have already been mentioned under training and supply, but others are equally capable of benefitting from skillful medium-range or extended-range forecasts.

Energy (power and heat) requirement forecasts are an obvious application. When to secure steam for the season is a regular question each spring at large naval bases. When to shift to the summer (or winter) uniform is another which involves comfort and morale. When to schedule an overhaul on a peak-load or standby air conditioning compressor is another example. An early alert as to when the motorpool should be winterized would also be well received.

Construction projects - grading, painting, underground cable laying, etc. - are often scheduled well in advance and are more easily and economically rescheduled a week ahead than a day ahead. Waterside and underwater construction projects so often

problem is presented by coordinated, multi-command, joint or combined training exercises. These are exercises where the the staging expenses and transport costs are substantial, and where the flexibility in operating area and rendezvous point choices is extremely limited as start time approaches. Permission may be required to use particular civilian or other country airfields or port facilities as alternates or staging areas. Air and sea navigation advisories may be more numerous. The safety, comfort and favorable impressions of VIP observers may well be involved. A few hundred miles adjustment of a firing area or the rescheduling of an underway replenishment, which could easily be made in the medium-range may become a cancellation or an embarrassing delay if only short-range guidance is available.

3.2.4 Supply and Logistics Applications. Here the subject is what gets delivered, where and when, and by what means. Again, the options and economies possible in the medium-range often disappear and become mere ways to cope in the short-range.

When Friday's arrival becomes Saturday's overtime it would be better to know it on Monday than on Thursday - especially when destination rather than enroute winds are the culprit and a Friday night lying-to offshore could have been traded for a more comfortable or economical voyage.

Arctic and Antarctic resupply is sea-ice sensitive. The ability to correctly forecast an early freeze or late breakup using longer-range wind and temperature forecasts would be highly useful.

The loading or offloading of nuclear weapons is a highly coordinated and involved procedure for which days-in-advance scheduling is required and "good" weather is always desired.

Many items of supply are labeled "store in a cool dry place"

Convoy routing submarine threat could benefit indirectly from longer-range atmospheric predictions when the results of such predictions are fed into ocean models. In Rosmond et al, (1983), it was concluded that "the greatest improvements in upper-ocean prediction will be achieved by improving the surface fluxes produced by the atmospheric models" and that "an immediate improvement in the prediction of SST (sea surface temperature) and MLD (mixed layer depth) ... on time scales of 15 days or less" would result.

3.2.3 <u>Training Applications</u>. Training activities are nearly continuous in the Navy and are large items in every budget. Except for classroom training, such activities are highly sensitive to environmental factors.

Much unit-level fleet training is conducted in specific beach, coastal and offshore areas which are subject to assignment and substantial controls for safety and efficiency reasons. Areas (or subareas) are assigned well in advance (several days to a week), schedules are published, and required services, such as tug-towed targets or tracking aircraft, are arranged. Assignment of areas (north or south, deep water or shallow, long transit or short transit) is flexible when "next weeks" schedule is prepared. However, when allocations have been made and notices to marines or airmen concerning ordnance firing and other hazards have been issued, it becomes difficult and expensive to make changes. There is nothing more frustrating than to depart at first light or steam all night for a ground-to-air gunnery exercise and then find the ceiling or visibility below safety minimums, or to schedule a full-power ship trial and find seas too rough for it to be carried out. The ability to confidently pick the most likely areas and/or the acceptable days for a particular type of training "next week" could in itself justify a major investment in longer-range forecasting.

A similar but potentially more expensive and frustrating

to infer probable conditions three days along a 10 to 15 day journey - just long enough to get the ship or group of ships started in the best direction (or, if the guidance proves wrong, toward trouble or onto a radical, fuel wasteful diversion to avoid mid or late voyage problems). The ship router is most interested in probable storm tracks and prevailing winds - the first to avoid serious slowing or damage and the second to recommend tracks which provide following seas for general fuel economy or head winds and favorable seas for economical enroute flight operations. Transits are monitored and later forecasts and guidance are used by the router to either adjust the track away from more hazardous or impeding conditions or to take advantage of more favorable forecast conditions and shorten the distance travelled.

Beside the basic least time, least fuel, no damage considerations in transit planning, there are other environment-sensitive elements to consider. Flight operations were mentioned earlier. These require at least ten knots of headwind, or the carrier and any escorts will have to use excessive speed or reverse course to obtain sufficient wind relative to the flight deck. Either action is very costly in terms of fuel. Besides moderate head winds, flight operations may require choosing a track close enough to an air field for use as an alternate. An example would be to choose a track within a few hundred miles north <u>or</u> south of the Azores.

Replenishment and/or training enroute can require choosing rendezvous times and points and exercise dates and areas several days in advance depending on preparation and transmit times for other participants. Wind and sea conditions can be favorable one day and not so the next, or they can impede the progress and delay the arrival of the participating units. In many cases the ability to confidently choose the least stormy of two or three alternative days would suffice.

numbers and in terms of flight and steaming hours available between periods of upkeep. Time on station is limited by fatigue factors and fuel capacity. Fuel itself is limited by depot stock on hand and budget considerations and similar limitations apply to other expendables such as sonobuoys and bathythermographs.

Knowing that high winds and seas associated with a storm will affect an ocean area in five days and will persist, a commander would be able to assign extra assets in order to localize a potential threat before the stormy period arrives. Likewise, a forecast break in an extended period of gales could permit planning an optimum time to concentrate search assets in some other high interest area.

Ocean Survey Scheduling. Ocean surveys often cover large areas and take many weeks or even months to complete. The effectiveness of both deep ocean and coastal survey operations could be increased by fine tuning schedules based on accurate medium and extended-range forecasts. Wind and sea forecasts could determine which side or sub-area of the survey area should be done first for maximum equipment efficiency, crew comfort and safety. Medium-range forecasts could determine when surf and visibility would be best for placing a survey assistance party ashore.

3.2.2 Transit Applications. Optimum Track Ship Routing (OTSR) or simply "ship routing" is perhaps the most obvious application for medium or extended-range products. It is also certainly the Navy's most regular user of available medium range forecasts and extended range guidance. Though it varies with ship type and the ports involved, most ocean crossings at an economical speed will take one to two weeks. The expected environmental conditions (principally winds and sea conditions) along a set of alternative routes are used to prescribe a "recommended track" 36 to 48 hours prior to the intended or recommended departure time. Thus a five-day forecast (the longest now available from FNOC) is used

Similarly, the scheduling of post-strike reconnaissance to assess damage is also influenced by weather. Decisions as to from where and when such reconnaissance should be flown against what targets will also depend on forecast over-target cloudiness and visibility.

Assault Planning. An amphibious or airborne assault over a beach is highly weather sensitive. This was true in Normandy and in the Falklands. A hurricane could have easily interfered with the Independence's transit to or from Grenada. Examples of preassault questions requiring medium range guidance include:

What subset of possible landing areas will be the most sheltered from wind and surf?

Where should equipment be prepositioned and when should it be preloaded to ensure safe arrival?

Will heavy equipment be transported by landing craft or airlifted ashore?

Will near-beach terrain be trafficable for all vehicles?

Must equipment and personnel be protected from freezing and frostbite?

Will winds permit precision airdrop from an acceptable altitude?

Are rain and/or fog likely to provide cover (or complicate navigation and communication)?

Undersea Surveillance Planning. Limited assets are available for detecting, locating and classifying subsurface targets in multiple, large, high-threat, ocean areas. Aircraft and ships available for search and localization are limited in

Arrival probability may be different for a self-guided, unmanned vehicle than for a manned aircraft depending on navigation systems installed, passive and active defensive measures, etc. Cloudiness and precipitation enroute may provide cover and increase likelihood of arrival for one delivery system but cause another system to loose its way.

Delivery probability will vary among guidance systems as their sensitivities to target area cloudiness, visibility and temperature vary. The effectiveness of enemy defenses may or may not be affected in an offsetting direction.

In the case of manned delivery platforms, probability of recovery for another mission becomes an important factor. This is influenced by weather enroute to and at the post-strike recovery site (which may be an alternate).

The final choice of penetration and delivery tactics (for example, jammers and altitude) and maybe even choosing between primary and alternate targets or recovery sites can all await the pre-launch, short-range weather forecast. But, several days to a week or more in advance, when deadlines arrive for choosing between possible launch sites and for prepositioning ordinance and delivery systems, medium-range forecasts with skill better than climatology could substantially increase the prospects of launching the right vehicle, with the right weapon, from the right location against the right target.

Reconnaissance Scheduling. Aerial or space reconnaissance to locate and confirm targets is f· uently desired as late as possible before some future date. A photo taken one day before a strike may be best, but one a week old is better than none at all. Medium range forecasts must be used to determine the latest likely period when cloud cover and visibility conditions will be acceptable for a given mission.

3.2.1 Mission Planning Applications. To place this category in perspective one should distinguish long-term mission planning from near-term mission planning. The former is done months or even years in advance. Various options and contingencies are considered and weighted according to the relative risks and probabilities of success. Environmental factors in long-range planning are based on climatological frequencies, means and extremes. As the planned or proposed mission execution date(s) approach to within a few days or a week or two, or as a given contingency becomes much more likely and immediate, long-range plans require near-term tuning. This near-term planning typically involves eliminating the higher risk options and increasing success expectancy. This is when the near-term planner needs to know which direction the "weathers" departure from normal will take and, if possible, some estimate of the magnitude. Nearly all high risk, non-routine missions could benefit from skillful medium or extended-range forecast information. The examples below are typical. Other more routine missions like transits and resupply are treated separately in later paragraphs.

Target Assignment. Long-term strike planning involves the delivery of a mix of weapons on a mix of targets with a mix of delivery platforms traversing a mix of penetration routes. Probability of success is determined among other things by using climatology to assess the probability of launch (take-off weather sensitive), probability of arrival (enroute weather sensitive), and probability of weapon delivery on or sufficiently near the target (target weather sensitive).

Launch probability is obviously different for a fixed-site missile than for a carrier launched aircraft - especially when one must consider the probability of the carrier arriving on time at the intended (or at an acceptable) launch point. Storminess enroute to or at this launch point can be a significant factor.

This lack of detailed requirements reflects a natural tendency to not request that which is considered unavailable. The operational forecaster who witnesses and demands increasing short-range forecast skill may not realize that such a capability may portend some acceptable skill in a medium-range product. Publishing this study and presentations to senior Naval Officers regarding the potential availability and applications of medium-range forecasts should lead to new and more definitive statements of requirement.

This section discusses a number of longer-range forecast applications as well as the parameters involved and the form such forecasts should probably take. Benefits to be derived are also discussed.

3.2 Applications. Practically all Navy operations and functions contain weather-sensitive elements of risk and involve alternatives which are influenced by environmental factors, but not all of these operations would benefit from medium-range or extended-range forecasts. Today is obviously soon enough to concern ourselves with possible alternates, with enroute winds and temperature and with the resultant fuel load for a cross-country flight planned for tomorrow. The operations and evolutions which can most benefit from longer-range forecasts are typically those of a long duration (for example, a transocean voyage), those involving complex preplanning and/or prepositioning (for example, a joint or combined exercise), those which are highly discretionary with respect to scheduling (for example, a taxiway resurfacing which could be done "anytime this month") and those involving large elements of risk to personnel and/or property (for example, a space shuttle mission). Such applications are discussed below and broadly categorized. In some cases, however, the category is rather arbitrary since, for example, training today may be wartime mission planning tomorrow.

One way previously mentioned and the best way is to apply a prior skill-based bias and standard deviation to the current point-in-time-and-space model output. A second way would be to consider the range of values calculated for the point in question during some number of time steps bracketing the time in question. A third way would be to consider the range of values contained in an ensemble of forecasts verifying at the same time but computed from initial conditions at different observing times (lagged unaveraged forecasting!). A fourth way would be to consider the range of values calculated for the time in question at several gridpoints surrounding the point in question. There are other possibilities such as establishing the statistical variance of many sets of time and space means.

However it may be derived, any range-of-values forecast acknowledges that the model output has a practical precision limit. It seems reasonable and prudent to provide the forecast consumer with the statistically significant range(s) for his time, place and parameter(s). Such ranges explicitly stated in text, on labels or in a graphic products legend, will acquaint the new user with the longer-range products skill and help insure against misunderstanding the adjectives used and against misplaced confidence in the product as a categorical one. Such a policy will require a system of routine model output verification and skill assessment so that realistic value ranges can be assigned as a function of location and season and so these can be updated when the model is changed.

There are viable alternatives to discrete range-of-values, condition parameter forecasts. A time mean is one. For example, ECMWF routinely prepares a 500 millibar five-day mean forecast centered on day eight (hour 192). Such a product must be labeled to alert the consumer as to the averaged nature of the information and to the need for caution when applying the product because of the unstated variability. A time mean serves to filter out the higher frequency, shorter wave length "weather".

A similar, but perhaps more meaningful product than the time mean can be prepared by spectral truncation. As discussed in Section 2, longer-range predictions lose skill in the shorter wavelengths faster than in the longer wavelengths. Spectral truncation can therefore filter out the less from the more skillful. If wave numbers greater than say three or five or nine are filtered out of the forecast field, the residual looks much like a time mean. But a time series of spectral truncations has the advantage of capturing the evolution of the longer wave features. The time mean only captures a single, approximate, mid-period long wave position.

A space mean can provide valuable free atmosphere information. It may also be a valuable surface-level product for ocean areas, but surface space means are in general unexplored because of land/sea and local orographic differences which complicate any averaging process.

The departure from normal concept is frequently used to prepare, display and measure the skill of longer-range forecasts. If one knows the "normal" position of a "weather pattern" or a "storm track" determinator such as a long wave trough or ridge, and if one also has a forecast field from which to calculate the direction and magnitude of its displacement from the normal position; then, the direction and perhaps the magnitude of the weather anomaly can be assessed. The "near", "above", or "below normal" forecast can be made; <u>and</u> <u>if</u> it is correct <u>and</u> <u>if</u> the consumer knows what "normal" is <u>and</u> what "near" means, then he should be pleased. This general situation is reflected in the popularity and practicality of forecast verification schemes which measure a models ability to forecast departures from the monthly or seasonal climatological mean (its anomaly correlation). ECMWF, for example, considers a 50-60% anomaly correlation useful and an 80% correlation good. They consider the 50 to 60% limit of useful predictability justified by

comparisons with subjective assessments of the forecasts carried out by some of the ECMWF member states (Bengtsson, 1982a). This is probably a reasonable measure for most Navy applications.

One naval officer with considerable recent aircraft carrier and staff afloat forecasting experience estimated he spent about 75% of his time making three to seven day "planning forecasts". It was his observation that today's admiral, skipper or chief-of-staff understands the limit of categorical forecasts and that he is attuned to making decisions and to "having their weapon systems (their computer-based, fire-control systems) make decisions" based on uncertainties and probabilities. Variability, normal and departure from normal are part of their vocabularies and operating strategies. (It was suggested, however, that if the computer knows what the departure from normal is, that it is preferrable to have the computer perform the requisite addition or subtraction and distribute the result! This is a valid suggestion for any point forecast, but it is not for an area forecast of surface weather conditions where local variability in the "normal" is substantial.)

Of the several alternative product types discussed above, it is recommended that the emphasis be shifted from discrete range or precise adjective terminology, to departure from normal sense and approximate magnitude terms, and finally to the sign of the departure from normal only as the models skill decreases with forecast time. For example, a four to seven day forecast would be put in range or adjective terms, a seven to ten day forecast would be in sense and magnitude of departure form and any extended-range forecast would indicate only the probable sense of the departure from normal.

It is further recommended that longer-range forecasts not be stated in probabilistic terms like "60 percent chance of freezing" when such terminology can be avoided. This is because a forecast range like "temperature between 25 degrees and 35

degrees F" or even a previously defined "near freezing", if based on a ninety-plus percent confidence level, is potentially less misleading and certainly provides more information. An exception may be a forecast parameter such as precipitation, for which a "60 percent chance" would provide more information than a simple "rain" or "no rain". Even here, though, the accumulation over time as determined by the forecast model and rounded to a very few significant figures would provide more information.

The transmission and display format employed is probably not product dependent, but should be chosen for communications efficiency and intended customer convenience. A short narrative "extended outlook for next week: stormy early week, but clear and freezing midweek with more cloudiness and a warming trend by week's end" might serve well in a naval station newspaper or plan of the week. A contour chart of 500 millibar seven-day forecast versus normal geopotential height differences may be appropriate for use by an Oceanography Center meteorologist in preparing th station narrative forecast just described. But, a simple three color, three contour normal, above normal, below normal sea roughness outlook chart might best serve an operational commander afloat.

This subsection has tried to alert the modelers and product designers to two significant elements of any longer-range forecasting endeavor. First is the need to introduce some substantially different basic products - forward and backward in time averages and spectral truncations for example. Second is the need to gather and maintain verification data sufficient to define and refine the new and less precise terminology which will be used.

3.3.3 Accuracy. The previous subsection acknowledged decreasing prediction skill as length of the forecast period increases, but it did not address the more difficult question of how much (or little) skill, accuracy or precision is acceptable. Discussions

with experienced, operational Navy forecasters suggest that any skill over climatology as a basis for next week's forecast would be very useful; as would any skill over simple extrapolation of the trend from a short-range forecast.

"Accurate enough" in some tropical location where day-to-day variability is small is probably provided by persistence in the absence of a synoptic-scale system like a hurricane. But "accurate enough" at some exposed mid-latitude location, where winds, for example, can range from calm to fifty knots, may well be ±20 knots. For some other application wind magnitude may be unimportant but direction within ±45 degrees could be critical. In still another case ±90 degrees may suffice for ten-day planning, but ±20 degrees would be needed for five-day planning. Some fire control computers are programmed to consider short-range scalar wind forecasts to have an accuracy of ±14 knots and temperature forecasts to be within five degrees. If such tolerances are acceptable in short-range forecasts it is reasonable to assume similar accuracy would be acceptable for many medium-range applications.

Even though acceptable accuracy is highly system and situation dependent, an effort to establish some generally reasonable levels of medium-range forecast skill was made. This took the form of asking several experienced forecasters to review the applications discussed in subsection 3.2 and to then fill in a table of acceptable five-day and ten-day accuracy for the most important weather variables. Complete agreement was not obtained, but Table 3-02 reflects a reasonable consensus. In some cases, such as wind direction, a degree of accuracy is clearly stated. For other parameters, such as precipitation, a less than fully prescribed two or three category accuracy is indicated. In such cases the precise bounds of the category are not so important as long as they are documented. It is probably obvious that the limits of adjacent categories must also overlap.

WEATHER PARAMETER	ACCURACY AT FIVE DAYS	ACCURACY AT TEN DAYS
Extratropical Storm Track	200 nm avg. STE[1]	400 nm avg. STE[1]
Wind		
Sfc[2] speed	± 25%	± 50%
Sfc[2] direction	± 45 degrees	± 60 degrees
FA[3] speed	± 20%	± 40%
FA[3] direction	± 45 degrees	± 60 degrees
Temperature		
Sfc[2]	± SStdDev[4] · 0.4	± SStdDev[4] · 0.7
FA[3]	± 5°C	± 10°C
Clouds		
cover	± 25% (± 2/8)	clear or scattered/ broken or overcast
dominant type	cumuliform/mixed/ stratiform	cumuliform/mixed/ stratiform
base of dominant	low/middle/high	low/high
Precipitation	likely/possible/unlikely	likely/unlikely
amount (if likely/possible)	light/moderate/heavy	light/heavy
type (if likely/possible)	steady/mixed/showers	PNP[5]
frozen (if likely/possible)	yes/possible/no	likely/unlikely
Visibility	<3/3-6/>6 mi	PNP[5]
Waves (sea, swell & surf)	(sfc wind & geography dependent)	(sfc wind & geography dependent)

NOTES:

[1]STE is Surface Track Error; the minimum distance between forecast cyclone positions at prime synoptic times and the verifying cyclone track.

[2]Sfc is surface value at about two meters altitude.

[3]FA is free atmosphere above the planetary boundary layer.

[4]SStdDev is the Seasonal Standard Deviation.

[5]PNP means probably not predictable.

TABLE 3-12. Acceptable Levels of Accuracy.

Summarizing, beyond ensuring that short-term skill over persistence and long-term skill over climatology is provided, it is probably most important that this skill be documented for the user and that model output not be presented in terms more precise than the documented skill will support. A time-step, gridpoint value of 72 degrees F must be converted in any end-product forecast to a "sixties or seventies" if the models standard error is ten degrees for that particular location and month or season.

3.4 Benefits. In subsection 3.2 many potential applications for longer-range forecasts were discussed but no price was placed on the benefits to be derived from such predictions.

There were studies in the sixties which documented the several million dollars worth of fuel saved by the Military Sea Transportation Service (MSTS) as a direct result of more efficient voyage planning and execution with the Navy's then new OTSR service. At that time MSTS (now the Military Sealift Command) had an extensive, regular transocean passenger ship schedule and it was possible to compare directly several pre-OTSR years with the first OTSR years. Since that time, for lack of solid data, similar studies have been able to do little more than estimate based on what might have happened - how much more fuel, how much more time, how much more ship and cargo damage, how many more injuries, how much more discomfort and how much less efficiency.

Again, though such "might haves" cannot be substantiated, it is inescapable that the annual expense of preparing and distributing medium-range forecast guidance could be more than offset by avoiding the loss of one aircraft or by escaping severe storm damage to one ship. Obviously one life saved or one additional critical mission successfully accomplished would also justify an investment in more skillful planning through the use of medium-range forecasts.

It is also probably irrefutable that the value of any forecast is inversely proportional to the number of opportunities remaining to change one's mind. Thus the last-chance, readyroom forecast prior to launch had better be correct, but the climatology-based, early planning outlook for next months training schedule can be revised once or twice without serious consequence. This, together with the additional computer time required to prepare an extended-range forecast, the communications time required to distribute it, and the marginal skill likely to be obtained with the present generation of prediction models - all of these - lead to the conclusion that for now the benefits to be derived from extended-range (10-15 day) forecasts are not sufficient to justify the cost. This position should be reconsidered whenever model developers can demonstrate extended-range skill which is clearly better than climatology.

Finally, the benefits to be derived from a medium-range forecast product depend to a considerable extent on when it is prepared and made available. This is particularly true in "peace time" when much high-level planning is conducted during a fairly normal five day work week. A forecast received at night or on the weekend is likely to grow old before it is seriously considered. Similarly, because few planning applications require or warrant daily reconsideration, a new longer-range product each day from Monday through Friday is overkill. This leads to the conclusion that a "this weeks" ten day forecast prepared on Sunday night and available early Monday morning (East Coast time), a "next weeks" ten day forecast prepared on Tuesday for Wednesday morning consideration, and a "rest easy" ten day forecast prepared Thursday night for Friday morning consideration would be sufficient for most Navy applications. There may, however, be good and sufficient verification and diagnostic reasons to run the medium-range model daily even if the results are not distributed beyond Monterey. Such determinations will be more easily made after a comprehensive model evaluation.

SECTION 4. OCEANOGRAPHY COMMAND CONSIDERATIONS

4.1 Introduction. If the Navy is to have an operational medium-range forecast capability, there are a number of important considerations beyond model formulation and development, skill assessment and application or user identification. New products and new packaging will be required for new applications. Considerable planning, software development, testing, documentation and training will be required before these new products can become operational. The effects of a commitment to medium-range forecasting will not be limited to the central site, FNOC, but will be felt throughout the Naval Oceanography Command. Such considerations are highlighted in this section.

4.2 Central Site Considerations. Since it is assumed in this report that any medium-range forecast system would be routinely executed at Fleet Numerical Oceanography Center (FNOC), Monterey, California; this paragraph applies principally to FNOC. There are, however, aspects which may require coordination with and the attention of other Monterey activities such as the Naval Environmental Prediction Research Facility (NEPRF), the prediction model developer, and the Naval Telecommunications Command Center (NTCC), which may be involved in product distribution.

4.2.1 Central Site Hardware. The present global forecast capability is provided by the Navy Operational Global Atmospheric Prediction System (NOGAPS), which has been operational at FNOC since August 1982. NOGAPS is integrated to 120 hours (five days) seven days a week using the 00Z analysis and to 72 hours each day using the 12Z analysis. A far larger number of day-four and day-five fields are produced than are actually distributed as "products". To run NOGAPS on FNOC's Control Data Corporation (CDC) Cyber 205 computer now averages 36 minutes (Cyber 730 wall-clock time) per forecast day for the first three days of the forecast and 23 minutes per forecast day for days 4 and 5 of the

forecast or 155 minutes for all five days. These times do not include the time required for the two 6-hour data assimilation analysis and forecast model initialization cycles; nor the CDC Cyber 730 computation time required for postprocessing approximately 670 spherical forecast fields (614 fields through day 3 plus 56 fields for days 4 and 5).

If a decision were made to integrate the 9-layer NOGAPS to ten rather than 5 days with the 00Z data, the preprocessing and data assimilation time would remain the same and 205 integration time should be about 270 minutes (about 1.75 times the 5-day minutes). This estimate is based upon the execution time from tau 72 to tau 120 being applicable for the running time from tau 120 to tau 240. The amount of postprocessing time is problematical since it would depend upon the number and nature of the medium-range products being generated. However, the time required for any space or time averaging, or for accumulating from multiple output fields, would probably be offset by fewer total fields and products to be prepared for the second five days. Routine verification and diagnostic summaries would require more computer time.

During December 1983 it was estimated that up to six hours of wall-clock time on the Cyber 205 could be made available during the 00Z watch for operational meteorological medium-range prediction. This is more than sufficient for present operations, but the full impact of global oceanographic prediction is not yet known. When the second segment of the vector processor in the 205 is activated and the additional half-million words of central memory become available in 1985, execution time of the then operational NOGAPS should decrease about 10%.

The postprocessing situation is encouraging with a firm plan to improve the existing system by means of the PEPS (Primary Environmental Processing System) Upgrade. This plan calls for incrementally replacing three 6500's and the 730 with CDC Cyber

855 equipment during 1984 and 1985. Even the first 855 which is scheduled to arrive in the spring of 1984, should go far toward providing the postprocessing capability necessary for a medium-range system. However, until this first increment of PEPS Upgrade is in place, it is unlikely that any substantial verification or diagnostics package could be run on an in-line, production basis. This is particularly true if the SPC is again processing a normal load of satellite data.

In summary, there will be enough forecast model integration time and processing power available in the near future and this availability should improve with time.

<u>4.2.2 Central Site Software</u>. Most of the software changes and additions which would be required for medium-range forecasting are relatively straight forward, but in any system as complex as NOGAPS and in operations as tightly knit as FNOC's, no change of this magnitude is trivial. Longer model integrations would require revised job control procedures and computer operator instructions. Product preparation check-off lists would require revision as would transmission schedules. Other non-computer "software" such as product catalogs will need to be expanded.

In a more traditional software sense, new and different medium-range summary products will require new postprocessor software. When such software is capable of producing, for example, a spectral truncation over the desired area for the desired day on the desired map background, a product identifier and distribution schedule will need to be specified.

Perhaps the most demanding software product will be that associated with routinely verifying model output and statistically reducing this data for skill assessment and documentation purposes. Trade-offs between archive size and future output data value will have to be made. Choices between substantial regular daily data reduction and less frequent, off-

time reduction will have to be made. Reliability, flexibility and efficiency will all be required. The reader is referred to Arpe (1981) for a detailed discussion of the ECMWF verification and diagnostics package which could well serve as a model for the Navy; particularly since the Evaluation of SEASAT Data Assimilation Statistical Analysis System (ESDASAS) is already installed at the FNOC. The ESDASAS includes the verifications described in the ECMWF Technical Report No. 1 for spectral evaluation in terms of root-mean-square-error, correlation coefficients, kinetic energy, zonal to eddy kinetic energy transfer, eddy available potential energy, zonal available potential energy, and zonal to eddy available potential energy transfer. ESDASAS also provides Hovmoller diagrams as suggested by Richard C. J. Somerville when he was with the National Center for Atmospheric Research (NCAR) and includes a standard statistical package for field to field and field to spot-data evaluations and verifications.

4.3 Other Site Considerations. The Navy Oceanography Command, both the headquarters and its field activities, will have a major role in providing longer range forecasts to satisfy Navy applications.

The first problem will be coordinating and agreeing on which forecast variables are to be provided and in what format the new products will be presented. For example, should the "500 mb next week product" be a day-eight spectral truncation (how many wave numbers?) of heights or should it be a time average (over how many days?). Or, should precipitation be summarized in inches or adjectives and in how many categories with what definition to satisfy the most (or most important?) customers?

A second major undertaking is the drafting, coordination and issuance of revised NEDN and AWN transmission schedules and revised fleet facsimile broadcast schedules to accommodate these new products. New AWN bulletin headings (MANOPS) will need to be

coordinated with the Air Force. Communication tables of required fields and products by user activity will need further expansion or revision.

Perhaps the greatest challenge will be instructing the geophysics officers in the fleet _and_ the warfare specialist end-users in the interpretation and application of longer-range forecast products. These instructions should be detailed, standardized in writing, and also discussed in training seminars. Murphy and Brown (1983) have shown that even familiar, short-range forecasting terms and phrases are subject to different and sometimes very wide-ranging interpretations, both among meteorologists and non-meteorologists. New "non-traditional" products should not be distributed nor used operationally until the likelihood of misinterpretation and misapplication has been minimized.

SECTION 5. PRINCIPAL CONCLUSIONS AND RECOMMENDATION

Based on the review of medium and extended-range forecasting contained in Section 2 of this report, on the description of uses for longer-range numerical forecasts contained in Section 3 and on the several Oceanography Command considerations identified in Section 4, the following is concluded:

- Based on both theoretical studies and on the considerable operational experience at ECMWF, skillful medium-range forecasts are now possible - but this skill will vary significantly both geographically and seasonally (see subsection 2.3).

- It has been demonstrated that the skill of most present numerical models, including NOGAPS, could be improved by eliminating the source of systematic errors, particularly in the tropics, or by compensating for the errors by postprocessing the model output (see subsections 2.4 and 2.5).

- Based on theory and limited case studies, there is good reason to conclude that models and forecast systems yet to be developed will provide useful forecast skill in the extended range - but such skill will be more general and probably limited, for example, to predicting only the planetary waves (see subsection 2.6).

- Though most of the Navy's requirements are not formally stated, there are many and varied applications for and benefits to be derived by the Navy from longer-range forecasts - particularly in the 5 to 10 day range (see subsection 3.2).

- Longer-range forecasts will be stated and displayed in ways substantially different from those now used for

short-range forecasts (see subsection 3.3).

- Any operational longer-range forecast "system" must include routine model output verification and skill assessment - both geographically and seasonally (see subsection 3.3).

- Though highly situation dependent, it is possible to establish generally acceptable levels of accuracy for medium-range forecasts (see subsection 3.4).

- There are sufficient computer hardware resources available or planned for upgrade and replacement at the FNOC to initiate a medium-range meteorological prediction capability during 1984/1985 (see subsection 4.2).

- Any commitment to provide medium-range forecasts will require a significant Oceanography Command investment in new support software, new product documentation, forecaster training and end-user indoctrination (see subsection 4.3).

Accordingly, it is recommended that that Navy proceed with a comprehensive evaluation of the 9-layer NOGAPS as a medium-range (5 to 10 day) forecasting system.

REFERENCES

Akesson, O., H. Bottger, and H. Pumpel, 1982: First results of direct model output verification of near-surface weather parameters at 17 locations in Europe. ECMWF Operations Dept. Tech. Memo. No. 55, 46 pp.

Akesson, O., 1981: Evaluation of the ECMWF operational model precipitation forecast in October-November 1980. ECMWF Operations Dept. Tech. Memo. No. 24, 17 pp.

American Meteorological Society, 1983: Proc. First Conference on Southern Hemisphere Meteorology, Sao Jose dos, Campos, Brazil, July 1983.

Anthes, R.A., 1983: Regional models of the atmosphere in middle latitudes. Mon. Wea. Rev., 111, 1306-1335.

Arpe, K., 1981: The verification and diagnostics package at ECMWF. Diagnostics of Diabatic Processes, 1980 ECMWF Workshop, 101-114.

Baker, W.E., and J. Paegle, 1983: The influence of the tropics on the prediction of ultralong waves. Part I: Tropical wind field. Mon. Wea. Rev., 111, 1341-1355.

Barnett, T.P., and R.C.J. Somerville, 1983: Advances in short-term climate prediction. Rev. Geophys. and Space Physics, 21, 1096-1102.

Bengtsson, L., 1981a: Numerical prediction of atmospheric blocking - a case study. Tellus, 33, 19-42.

Bengtsson, L., 1981b: Medium-range forecasting at ECMWF and remaining problems. Proc. Symposium Current Problems of Weather Forecasting. Wien, June 1981, Publication 253, 115-124.

Bengtsson, L., 1982a: Performance and limits of global models in the Mediterranean. Rivista Di Meteorologia Aeronautica, 42, 123-141.

Bengtsson, L., 1982b: Review of recent progress made in medium range weather forecasting. Problems and Prospects in Long and Medium Range Weather Forecasting, 1981 Seminar ECMWF, 91-112.

Bengtsson, L., M. Kanamitsu, P. Kallberg and S. Uppala, 1982: Diagnostic and predictability studies using FGGE data. Problems and Prospects in Long and Medium Range Weather Forecasting, 1981 ECMWF Seminar, 405-428.

Bottger, H., and S. Gronaas, 1982: Optimal verification of ECMWF surface temperature forecasts at two locations in Europe. ECMWF Operations Dept. Tech. Memo. No. 64, 26 pp.

Cats, G.J., 1982: Current problems in medium-range forecasting at ECMWF: Data Assimilation scheme. Problems and Prospects in Long and Medium Range Weather Forecasting, 1981 ECMWF Seminar, 141-182.

Charney, J.C., and J. Shukla, 1981: Predictability of Monsoons. Monsoon Dynamimcs, J. Lighthill and R.P. Pearce (eds), Cambridge Univ. Press, 99-109.

Cubasch, U., 1983: Sensitivity of the ECMWF model to changes in resolution. Intercomparison of Large-Scale Models Used for Extended Range Forecasts, 1982 ECMWF Workshop, 435-453.

Derome, J., 1981: On the average errors of an ensemble of forecasts. Atmos.-Ocean, 19, 103-127.

Doos, B.R., 1970: Numerical experimentation related to GARP. GARP Publication Series No. 6, 68 pp.

ECMWF, 1981a: Workshop on Diagnostics of Diabatic Processes, September 1980.

ECMWF, 1981b: Workshop on Tropical Meteorology and its Effects on Medium-range Weather Prediction at Middle Latitudes.. March 1981, 252 pp.

ECMWF, 1982: Seminar on Problems and Prospects in Long and Medium-range Weather Forecasting. September 1981, 428 pp.

ECMWF, 1983a: Workshop on Intercomparison of Large-scale Models Used for Extended Range Forecasts. June 1982, 464 pp.

ECMWF, 1983b: Seminar on Interpretation of Numerical Weather Prediction Products. December 1982, (in press).

Elsberry, R.L., R.L. Haney, R.T. Williams, R.S. Bogart, H.D. Hamilton, and E.F. Hinson, 1982: Ocean/troposphere/stratosphere forecast systems: A state-of-the-art review. Tech. Rep. CR 82-04. Systems and Applied Sciences Corp., 570 Casanova Avenue, Monterey, CA, 79 pp.

Egger, J., and H.D. Schilling, 1983: Error estimates for extended range forecasts with dynamic models. Intercomparison of Large-scale Models Used for Extended Range Forecasts, 1982 ECMWF Workshop, 69-80.

Gilchrist, A., 1977: An experiment in extended range prediction using a general circulation model and including the influence of sea-surface temperature anomalies. <u>Beitr. Phys. Atmos.</u>, <u>50</u>, 25-40.

Gilchrist, A., 1982: Long Range Forecasting in the meteorological office, Part I. Problems and Prospects in Long and Medium Range Weather Forecasting, 1981 ECMWF Seminar, 21-51.

Girard, C., and M. Jarraud, 1982: Short and medium range forecast differences between a spectral and grid point model. An extensive quasi-operational comparison. ECMWF Tech. Rpt. No. 32, 178 pp.

Harnack, R.P., 1981: Principles and methods of extended period forecasting in the United States. National Weather Association Monograph 1-81 (ISSN 0271-1044), 37 pp.

Haseler, T., 1982: An investigation of the impact at middle and high latitudes of tropical forecast errors. ECMWF Tech. Rep. No. 31, 40 pp.

Heckley, W., 1983: On the performance of the ECMWF model in the tropics. Intercomparison of Large-scale Models Used for Extended Range Forecasts, 1982 ECMWF Workshop, 315-370.

Hoffman, R.N., and E. Kalnay-Rivas, 1983: Lagged averaged forecasting, an alternative to Monte Carlo forecasting. Tellus, 35A, 100-118.

Hollingsworth, A., K. Arpe, M. Tiedtke, M. Capaldo, and H. Savijarvi, 1980: The performance of a medium range forecast model in winter - Impact of physical parameterizations. Mon. Wea. Rev., 108, 1736-1773.

Hollingsworth, A., and G. Cats, 1981: Initialization in the tropics. Tropical Meteorology and its Effects on Medium Range Weather Prediction at Middle Latitudes, 1981 ECMWF Workshop, 105-141.

Horel, J.D., and J.M. Wallace, 1981: Planetary scale of atmospheric phenomena associated with the Southern Oscillation. Mon. Wea. Rev., 109, 813-829.

Hoskins, B.J., and D. Karoly, 1981: The steady linear responce of a spherical atmosphere to thermal and orographic forcing. J. Atmos. Sci., 38, 1179-1196.

Jarraud, M., C. Girard and U. Cubasch, 1981: Comparison of medium range forecasts made with models using spectral or finite difference techniques in the horizontal. ECMWF Tech. Rep. No. 23, 96 pp.

Ji, L.R., and S. Tibaldi, 1982: Numerical simulations of a case of blocking: The effects of orography and land-sea contrast. ECMWF Tech. Rep. No. 33, 50 pp.

Johannessen, K.R., 1982: Verification of ECMWF quantitative precipitation forecasts over Europe from January 1980 to April 1981. ECMWF Research Dept. Tech. Memo. No. 51, 71 pp.

Kallberg, P., S. Uppala, N. Gustafsson, and J. Pailleux, 1982: The impact of cloud track wind data or global analyses and medium range forecasts. ECMWF Tech. Rep. No. 34, 60 pp.

Krishnamurti, T.N., H.L. Pan, C.B. Chang, J. Ploskey, D. Walker and A.W. Oodally, 1979: Numerical weather prediction for GATE. Q. J. Roy. Met. Soc., 105, 919-1010.

Krishnamurti, T.N., and V. Ramanathan, 1981: Sensitivity experiments on the monsoon onset to differential heating. Tropical Meteorology and Its Effects on Medium Range Weather Prediction at Middle Latitudes, 1981 ECMWF Workshop, 163-206.

Lambert, S.J., and P.E. Merilees, 1978: A study of planetary wave errors in spectral numerical weather prediction models. Atmosphere-Ocean, 16, 197-211.

Leith, C.E., 1974: Theoretical skill of Monte Carlo forecasts. Mon. Wea. Rev., 102, 409-418.

Leith, C.E., 1978: Predictability of climate. Nature, 276, 352-355.

Leith, C.E., and R.H. Kraichnan, 1972: Predictability of turbulent flow. J. Atmos. Sci., 29, 1041-1058.

Lorenz, E.N., 1969a: The predictability of a flow which possesses many scales of motion. Tellus, 21, 289-307.

Lorenz, E.N., 1969b: Atmospheric predictability as revealed by naturally occurring analogues. J. Atmos. Sci., 26, 636-646.

Lorenz, E.N., 1972: Barotropic instability of Rossby wave motion. J. Atmos. Sci., 29, 258-264.

Lorenz, E.N., 1982a: Some aspects of atmospheric predictability. Problems and Prospects in Long and Medium Range Weather Forecasts, 1981 ECMWF Seminar, pp 1-20.

Lorenz, E.N., 1982b: Atmospheric predictability experiments with a large numerical model. Tellus, 34, 505-513.

Madden, R.A., 1982a: Estimates of an unpredictable part of time-averaged meteorological data. Problems and Prospects in Long and Medium Range Weather Predictions, 1981 ECMWF Seminar, 335-347.

Madden, R.A., 1982b: A quantitative approach to long-range prediction. Problems and Prospects in Long and Medium Range Weather Predictions, 1981 ECMWF Seminar, 349-360.

Madden, R.A., 1983: Reply to comments on "Natural variability and predictability". Mon. Wea. Rev., 111, 586-589.

Madden, R.A., and D.J. Shea, 1978: Estimates of the natural variability of time-averaged temperatures over the United States. Mon. Wea. Rev., 106, 1695-1703.

Miyakoda, K., G.D. Hembree, R.F. Strickler and I. Shulmen, 1972: Cumulative results of extended forecast experiments. Part I. Model performance for winter cases. Mon. Wea. Rev., 100, 836-855.

Miyakoda, K., G.D. Hembree and R.F. Strickler, 1979: Part 2. Model performance for summer cases. Mon. Wea. Rev., 107, 395-420.

Miyakoda, K., and R.F. Strickler, 1981: Cumulative results of extended forecast experiments. Part III. Precipitation. Mon. Wea. Rev., 830-842.

Miyakoda, K., and J.P. Chao, 1982: Essay on dynamical long-range forecasts of atmospheric circulation. J. Met. Soc. Japan, 60, 292-308.

Miyakoda, K., T. Gordon, R. Caverly, W. Stern, and J. Sirutis, 1983: Simulation of a blocking event in January, 1977. Mon. Wea. Rev., 111, 846-869.

Moura, A.D. and J. Shukla, 1981: On the dynamics of droughts in Northern Brazil: Observations, theory and numerical experiments with a general circulation model. J. Atmos. Sci., 38, 2653-2675.

Murphy, A.H. and B.G. Brown, 1983: Interpretation of some terms and phrases in public weather forecasts. Bull. Amer. Meteor. Soc., 64, 1283-1289.

Namias, J., 1981: State of the art of predicting short period climatic variations. Food-Climate Interactions, W. Bach, J. Pankrath, and S.H. Schneider (eds.), D. Reidel Publishing Company, 399-422.

Namias, J., and D.R. Cayon, 1981: Large-scale air-sea interactions and short-period climatic fluctuation. Science, 214, 869-876.

Nicholls, N., 1980: Long-range weather forecasting: Value, status and prospects. Rev. Geophys. and Space Physics, 18, 771-788.

Nieminen, R., 1983: Operational verification of ECMWF forecast fields and results for 1980-81. Tech. Rep. No. 36, ECMWF, 47 pp.

Oriol, E., 1982: Energy budget calculations at ECMWF, Part I. Analyses 1980-81. ECMWF Tech. Rep. No. 35., 113 pp.

Paegle, J., and W.E. Baker, 1983: The influence of the tropics on the prediction of ultralong waves. Part II: Latent heating. Mon. Wea. Rev., 111, 1356-1371.

Pumpel, H., 1982: Regional and local verification of near surface weather parameters. 1982 ECMWF Seminar, (In press).

Ramanathan, V., 1983: The role of radiation in the zonal mean circulation: GCM experiments. Intercomparison of Large-Scale Models Used for Extended Range Forecasts, 1982 ECMWF Workshop, 95-105.

Ramanathan, V., E.J. Pitcher, R.C. Malone, and M.L. Blackmon, 1982: The response of a spectral general circulation model to refinements in radiative processes. J. Atmos. Sci., (In press).

Randall, D.A., 1982: Performance of the PBL parameterization in the GLAS and UCLA models. Proceeding of the Workshop on the Planetary Boundary Layer of the ECMWF Forecasts, 81-118.

Randall, D.A., 1983: Monthly and seasonal simulations with the GLAS climate model. Intercomparison of Large-Scale Models Used for Extended Range Forecasts, 1982 ECMWF Workshop, 107-166.

Robinson, G.D., 1967: Some current projects for global meteorological observation and experiment. Quart. J. Roy. Meteor. Soc., 43, 409-418.

Rosmond, T.E., A.I. Weinstein and S.A. Piacsek, 1983: Coupled ocean-atmospheric modeling for 3-15 day numerical prediction: A workshop report. NAVENVPREDRSCHFAC Tech. Rep. TR 83-05, 88 pp.

Rowntree, P., 1983: Sensitivity of general circulation models to land surface processes. Intercomparison of Large-Scale Models Used for Extended Range Forecasts, 1982 ECMWF Workshop, 225-262.

Savijarvi, H., 1981: The energy budgets in North America, North Atlantic and Europe based on ECMWF analyses and forecasts. ECMWF Tech. Rep. No. 27, 35 pp.

Shaw, D.B., 1981: ECMWF operational forecasts in the SW and NE monsoon regions. Tropical Meteorology and its Effects on Medium Range Weather Prediction at Middle Latitudes, 1981 ECMWF Workshop, 53-86.

Shukla, J., 1981: Dynamical prediction of monthly means. J. Atmos. Sci., 38, 2547-2572.

Shukla, J., 1983: Comments on "Natural Variability and Predictability", Mon. Wea. Rev., 111, 581-585.

Simmons, A.J., 1981: Tropical influences on stationary wave motion in middle and high latitudes. ECMWF Tech. Rep. No. 26, 57 pp.

Simmons, A.J., 1982: Current problems in medium-range forecasting at ECMWF: Model aspects. Problems and Prospects in Long and Medium Range Weather Forecasting, 1981 ECMWF Seminar, 113-140.

Simmons, A.J., and B. Hoskins, 1979: The downstream and upstream development of unstable baroclinic waves. J. Atmos. Sci., 36, 1239-1254.

Simmons, A.J., and R. Strufing, 1981: An energy and angular momentum conserving finite-difference scheme, hybrid coordinates and medium-range prediction. ECMWF Tech. Rep. No. 28, 68 pp.

Simmons, A.J., J.M. Wallace, and G.W. Branstator, 1983: Barotropic wave propagation and instability, and atmospheric teleconnection patterns. J. Atmos. Sci., 40, 1363-1392.

Smagorinsky, J., 1969: Problems and promises of deterministic extended-range forecasting. Bull. Amer. Meteor. Soc., 50, 286-311.

Somerville, R.C.J., 1980: Tropical influences on the predictability of ultralong waves. J. Atmos. Sci., 37, 1141-1156.

Spar, J., R. Atlas, and E. Kuo, 1976: Monthly mean forecast experiments with the GISS model. Mon. Wea. Rev., 104, 1215-1241.

Spar, J., J.J. Notario, and W.J. Quirk, 1978: An initial state perturbation experiment with the GISS model. Mon. Wea. Rev., 106, 89-100.

Spar, J., and R. Lutz, 1979: Simulations of the monthly mean atmosphere for February 1976 with the GISS model. Mon. Wea. Rev., 107, 181-192.

Tibaldi, S., and A. Buzzi, 1982: Orographic influences on Mediterranean lee cyclogenesis and European blocking in a global numerical model. ECMWF Tech. Rep. No. 29, 46 pp.

Tibaldi, S., and L.R. Ji, 1983: On the effect of model resolution on numerical simulation of blocking. Tellus, 35A, 28-38.

Tiedtke, M., 1983: Winter and summer simulations with the ECMWF model. Intercomparison of Large-Scale Models Used for Extended Range Forecasts, 1982 ECMWF Workshop, 263-314.

Wallace, J.M., and D.S. Gutzler, 1981: Teleconnections in the geopotential height field during the Northern Hemisphere winter. Mon. Wea. Rev., 109, 784-812.

Wallace, J.M., S. Tibaldi, and A.J. Simmons, 1983: Reduction of systematic forecast errors in the ECMWF model through the introduction of an envelope orography. Intercomparison of Large-Scale Models Used for Extended Range Forecasts, 1982 ECMWF Workshop, 371-434.

Webster, P.J., 1981: Mechanisms determining the atmospheric response to sea surface temperature anomalies. J. Atmos. Sci., 38, 554-571.

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